EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY

Leadership Under Challenge: Information Technology R&D in a Competitive World

An Assessment of the Federal Networking and Information Technology R&D Program

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About the President's Council of Advisors on Science and Technology

President Bush established the President's Council of Advisors on Science and Technology (PCAST) by Executive Order 13226 in September 2001. Under this Executive Order, PCAST "shall advise the President ... on matters involving science and technology policy," and "shall assist the National Science and Technology Council (NSTC) in securing private sector involvement in its activities." The NSTC is a Cabinet-level council that coordinates interagency research and development activities and science and technology policy-making processes across Federal departments and agencies.

PCAST enables the President to receive advice from the private sector, including the academic community, on important issues relevant to technology, scientific research, mathematics and science education, and other issues of national concern. The PCAST-NSTC link provides a mechanism to facilitate the public-private exchange of ideas that inform Federal science and technology policy-making processes.

As a private sector advisory committee, PCAST recommendations do not constitute Administration policy but rather provide advice to the Administration in the science and technology arena.

PCAST follows a tradition of Presidential advisory panels on science and technology dating back to Presidents Truman and Eisenhower. The Council's 34 members, appointed by the President, are drawn from industry, education and research institutions, and other nongovernmental organizations. In addition, the Director of the Office of Science and Technology Policy serves as PCAST's Co-Chair.

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Leadership Under Challenge: Information Technology R&D in a Competitive World

An Assessment of the Federal Networking and Information Technology R&D Program

President's Council of Advisors on Science and Technology

August 2007

EXECUTIVE OFFICE OF THE PRESIDENT
PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY
WASHINGTON, D.C. 20502

August 10, 2007

President George W. Bush
The White House
Washington, D.C. 20502

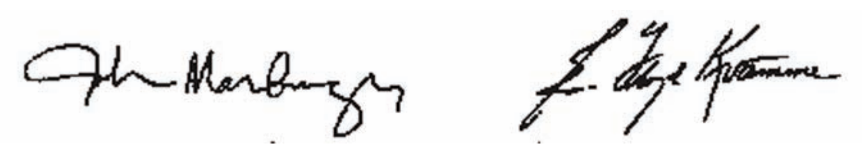
Dear Mr. President:

We are pleased to transmit to you a copy of *Leadership Under Challenge: Information Technology R&D in a Competitive World*. This report, prepared by your Council of Advisors on Science and Technology (PCAST), presents a formal assessment of the Federal Networking and Information Technology R&D (NITRD) Program, beginning with a review of global networking and information technology competitiveness. We examined the NITRD Program in the broader context of U.S. networking and information technology (NIT) leadership and global competitiveness in order to provide you with a current picture of the U.S. competitive stance and an evaluation of how well the NITRD Program is positioned to help sustain and strengthen U.S. leadership in these critical technologies.

While the United States clearly is the global NIT leader today, we face aggressive challenges from a growing list of competitors. To maintain – and extend – the Nation's competitive advantages, we must further improve the U.S. NIT ecosystem – the fabric made up of high-quality research and education institutions, an entrepreneurial culture, strong capital markets, commercialization pathways, and a skilled NIT workforce that fuels our technological leadership. The report highlights in particular the need to revolutionize postsecondary education and advanced training in NIT fields and to rebalance the Federal NIT R&D portfolio to emphasize more large-scale, long-term, multidisciplinary activities and visionary, high-payoff goals. We trust that our recommendations complement the goals and vision for leadership in the physical sciences articulated in your American Competitiveness Initiative.

We wish to recognize the leadership, commitment, and hard work of PCAST members Daniel A. Reed and George Scalise, who tirelessly guided the activities of the Subcommittee that led the development of our report. Please let us know if you have any questions about the activities of PCAST or about the report.

Sincerely,



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Executive Summary

The United States is today the global leader in networking and information technology (NIT). That leadership is essential to U.S. economic prosperity, security, and quality of life. The Nation's leadership position is the product of its entire NIT ecosystem, including its market position, commercialization system, and higher education and research system.

Other countries and regions have also recognized the value of NIT leadership and are mounting challenges. The challengers are not only established competitors in Asia and Western Europe but also newcomers such as India and China. Their methods include bolstering their overall NIT capacity, their institutions for educating NIT professionals, and their NIT research and development (R&D) programs.

This report addresses how the U.S. Government can support continued U.S. leadership in two components of the NIT ecosystem – NIT R&D and NIT education – through its investment in the Federal Networking and Information Technology Research and Development (NITRD) Program. Assessment of the NITRD Program is authorized in Federal law, and Executive Order 13385 assigned responsibility for this assessment to the PCAST.

The NITRD Program is a key mechanism through which the Federal government contributes to NIT R&D leadership. The NIT frontier remains full of opportunity: new NIT capabilities wait to be developed and integrated into products and processes to meet agency and national needs. In 2007, the Program is enabling more than a dozen Federal agencies to work together as they invest over $3 billion in R&D to meet their needs for advanced NIT capabilities.

This assessment benefited from responses to the PCAST's requests for input from a wide range of stakeholders in NIT R&D, including experts from academia and industry and Federal employees. A snapshot of the global NIT ecosystem was developed at PCAST request.

Based on these inputs, the PCAST found that the NITRD Program has by and large been effective at meeting agency and national needs. However, looking forward it is clear that changes are needed in order for the United States to ensure its continued leadership and ability to meet these needs. Specifically, the PCAST concluded that the most critical need is to rebalance the NITRD investment portfolio to include more long-term, large-scale, multidisciplinary NIT R&D and more visionary NIT R&D. The PCAST also believes that changes are needed in NIT education, the NIT workforce, the technical areas in which the NITRD Program invests, the rate of technology transfer, and the NITRD Program's planning and assessment processes.

The number of people completing NIT education programs and the usefulness of that education fall short of current and projected needs.

- *National Study:* The NITRD Subcommittee should charge the NITRD National Coordination Office (NCO) to commission one or more fast-track studies on the current state of and future requirements for NIT postsecondary education.
- *Visas:* The Federal government should:
    - Streamline the process for obtaining visas for non-U.S. students admitted to accredited graduate degree programs in NIT subjects.
    - Make it routine for foreign nationals who have obtained advanced degrees in NIT subjects at accredited U.S. universities to be permitted to work and gain citizenship in the United States by easing the visa and Green Card processes for them.

- *Fellowships:* The Federal government should increase the number of multiyear fellowships for graduate study by American citizens in NIT fields each year, with the target number and fields of such fellowships informed by needs identified in sources such as the national study on NIT education.

The Federal NIT R&D portfolio is currently imbalanced in favor of low-risk projects; too many are small-scale and short-term efforts. The number of large-scale, multidisciplinary activities with long time horizons is limited and visionary projects are few.

- *Federal Funding Programs:* Federal agencies should rebalance their NIT R&D funding portfolios by increasing:
  - Support for important NIT problems that require larger-scale, longer-term, multidisciplinary R&D
  - Emphasis on innovative and therefore higher-risk but potentially higher-payoff explorations
- *Government and Academia:* The Director of the Office of Science and Technology Policy (OSTP) should call on senior officials from Federal NIT R&D funding agencies and major research universities to address how to better conduct large-scale, long-term, multidisciplinary academic R&D in the development and application of networking and information technology important to the Nation.

As new funding becomes available, the following four areas should receive disproportionately larger increases because they address issues for which progress will have both the greatest effect on important applications and the highest leverage in advancing NIT capabilities.

- *NIT Systems Connected with the Physical World* (which are also called embedded, engineered, or cyber-physical systems): The NITRD Subcommittee should develop and implement a Federal Plan for high-confidence NIT systems connected with the physical world.
- *Software:* The NITRD Subcommittee should facilitate efforts by leaders from academia, industry, and government to identify critical issues in software design and development to help guide NITRD planning on software R&D.
- *Digital Data:* The Interagency Working Group on Digital Data, in cooperation with the NITRD Subcommittee, should develop a national strategy and develop and implement a plan to assure the long-term preservation, stewardship, and widespread availability of data important to science and technology.
- *Networking:* The PCAST endorses the ongoing effort to produce a Federal Plan for Advanced Networking Research and Development, expected in 2008, which includes an R&D agenda for upgrading the Internet and R&D in mobile networking technologies, and addresses network security and reliability.

To sustain the Nation's NIT leadership over the long term, the following four areas must continue as Federal R&D priorities.

- *High-End Computing (HEC):* The NITRD Subcommittee should develop, implement, and maintain a strategic plan and roadmap for Federal investments in HEC R&D, infrastructure, applications, and education and training.
- *Cyber Security and Information Assurance (CSIA):* The Federal NIT R&D agencies should give greater emphasis to fundamental, longer-term CSIA R&D and the infrastructure for CSIA R&D.
- *Human-Computer Interaction (HCI):* The Federal NIT R&D agencies should give greater emphasis to fundamental investigations of technologies and tools that make NIT systems easier to use by people, including those with specialized needs.

- *NIT and the Social Sciences:* The Federal NIT R&D agencies should continue to invest in this multidisciplinary field to inform public understanding of NIT's societal benefits and costs, guide policy making, and point to new directions for NIT R&D over all.

While in general the NITRD Program has effectively balanced agency needs with national needs and priorities, the current nature and scale of NITRD Program coordination processes are inadequate to meet anticipated national needs and to maintain U.S. leadership in an era of global NIT competitiveness.

- *Planning and Evaluation:* The NITRD Subcommittee should:
  - Develop, maintain, and implement a strategic plan for the NITRD Program
  - Conduct periodic assessments of the NITRD Program Component Areas and restructure the NITRD Program when warranted
  - Develop, maintain, and implement public R&D plans or roadmaps for key technical areas that require long-term interagency coordination and engagement
  - Develop a set of metrics and other indicators of progress for the NITRD Program, including an estimate of investments in basic and applied research, and use them to assess NITRD Program progress

NITRD National Coordination Office activities have resulted in increased NITRD interagency R&D coordination and planning.

- *Planning Support:* Under NITRD Subcommittee guidance, the NITRD NCO should develop and implement a plan for supporting the development, maintenance, and implementation of the NITRD strategic plan and R&D plans.
- *Communication:* The NITRD NCO should be more proactive in communicating with outside groups.

Introduction

It is difficult to overstate the contribution of networking and information technology (NIT) to America's security, economy, and quality of life. This contribution is the consequence of rapid advances in an array of technologies, some now ubiquitous, such as Internet search engines and wireless devices. Other technologies, such as simulation software and embedded systems, are essential to the effective performance of sectors that include national security, energy, health care, manufacturing, and transportation. The cumulative effect of these technologies on life in the United States and around the world has been profound and beneficial.

The success and impact of current NIT capabilities – such as the computer itself and the Internet – derive in considerable measure from the Federal government's early, substantial, and sustained investments in NIT research and development (R&D). Such investments remain a priority of the Federal government because of the prospects for continuing advances in NIT capabilities needed to support Federal agency missions and national priorities.

The High-Performance Computing Act of 1991 (Public Law 102-194) and the Next Generation Internet Research Act of 1998 (Public Law 105-305) mandate periodic assessments of what is now known as the Networking and Information Technology Research and Development (NITRD) Program, which encompasses nearly all of the Federal government's unclassified investments in NIT R&D. The legislation specifically calls for an independent assessment of:

(1) progress made in implementing the Networking and Information Technology Research and Development Program;

(2) the need to revise the Program;

(3) the balance among the components of the Program;

(4) whether the research and development undertaken pursuant to the Program is helping to maintain United States leadership in networking and information technology; and

(5) other issues identified by the Director of the Office of Science and Technology Policy.

The laws specify that the President shall establish an advisory committee, known as the President's Information Technology Advisory Committee (PITAC), to conduct these assessments. Executive Order 13385, signed September 29, 2005, assigns the PITAC's responsibilities to the President's Council of Advisors on Science and Technology (PCAST). To address the laws' requirements, in 2006 the PCAST initiated an assessment of the NITRD Program and formed the Subcommittee on NIT to lead the assessment.

The PCAST focused on U.S. leadership and competitiveness in networking and information technology as the context for assessing the NITRD Program. Investments in the NITRD Program contribute to a larger NIT system that includes research universities, firms that produce NIT capabilities, firms that use NIT capabilities, and the venture capital community, among others. It is the strength of this larger system – the NIT ecosystem – that underlies America's current global NIT leadership and competitive advantage. Therefore, a key aspect of this assessment is an examination of how well the NITRD Program contributes to the strength of the NIT ecosystem in the United States.

In conducting its assessment, the PCAST solicited the views of experts in a wide range of NIT fields. In particular, the PCAST created the NIT Technical Advisory Group (TAG), comprising 62 experts from academia

The NITRD Program

The NITRD Program[1] provides a framework and mechanisms for Federal agencies to set goals and coordinate their activities in NIT R&D. The Program has 13 member agencies with an annual aggregate budget of NITRD investments that now exceeds $3 billion. The goals of the NITRD Program are to:[2]

- Provide research and development foundations for assuring continued U.S. technological leadership in advanced networking, computing systems, software, and associated information technologies
- Provide research and development foundations for meeting the needs of the Federal government for advanced networking, computing systems, software, and associated information technologies
- Accelerate development and deployment of these technologies to maintain world leadership in science and technology; enhance national defense and national and homeland security; improve U.S. productivity and competitiveness and promote long-term economic growth; improve the health of the U.S. citizenry; protect the environment; improve education, training, and lifelong learning; and improve the quality of life.

The Program comprises eight subject-based Program Component Areas:

- High End Computing Infrastructure and Applications (HEC I&A)
- High End Computing Research and Development (HEC R&D)
- Cyber Security and Information Assurance (CSIA)
- Human-Computer Interaction and Information Management (HCI&IM)
- Large Scale Networking (LSN)
- High Confidence Software and Systems (HCSS)
- Social, Economic, and Workforce Implications of IT and IT Workforce Development (SEW)
- Software Design and Productivity (SDP)

and industry in a broad array of NIT specialties. The NIT TAG served as a source of technical information about current and anticipated NIT priorities, trends, and developments, and about Federal efforts and helpful measures in NIT. In addition, at the PCAST's request, the Science and Technology Policy Institute (STPI) of the Institute for Defense Analyses was commissioned to develop a snapshot of global NIT competitiveness as input to the assessment. STPI also conducted 39 interviews with stakeholders of the NITRD National Coordination Office (NCO), to solicit input on the effectiveness of the NCO in supporting the Program.

The PCAST also obtained information about the current state and future directions of NIT R&D from academic, industrial, and investment experts through panel sessions in Silicon Valley, Chicago, and Washington, D.C. To understand the present state and plans of the NITRD Program, the PCAST met with

[1] The NITRD Program is discussed in Chapter 5.

[2] From the *NITRD Program Supplement to the President's Budget*, FY 2007, National Science and Technology Council, Subcommittee on Networking and Information Technology R&D, Washington, D.C., February 2006.

representatives from NITRD member agencies. Literature surveys rounded out the PCAST's data collection activities. These diverse inputs complemented PCAST members' own expertise to provide the information base used to develop the report's findings and recommendations.

This report is organized into five chapters. Chapter 1 provides broad context by examining America's global leadership and competitive position in NIT as compared to major current and likely future competitor nations. Chapters 2 and 3 focus on central aspects of the U.S. NIT ecosystem: NIT education and training, the structure of the Federal NIT R&D portfolio, and technology transfer. In Chapter 4, the PCAST discusses specific NIT R&D areas that it has identified as priorities. The report concludes in Chapter 5 with an assessment of the mechanisms through which the NITRD Program is implemented.

Definition of Networking and Information Technology

"Networking and Information Technology" comprises the processing and communication of data and information and the hardware, software, and systems that perform those functions.

Hardware refers to computers and their components. It includes microprocessors, memory, storage media, displays, personal computers, servers, embedded devices, and supercomputers, and also includes communications channels and equipment for both wired and wireless networks.

Software refers to the instructions and associated information that control the operations of computers and their components. It includes firmware, systems software, programming software (including programming languages and compilers), and software development environments. It also includes application software for data and information capture, creation, manipulation, modification, transmission, storage, search, access or retrieval, and visualization.

Systems are combinations of hardware and software that perform processing and communication functions.

Examples of *processing and communication* functions are information storage and retrieval, mathematical computation, data visualization, transaction processing, Internet search, and streaming media.

Examples of *data and information* are characters, still images, audio, and video. They can be organized in structures such as databases, documents, and file systems.

CHAPTER 1

Global Competitiveness in Networking and Information Technology

Leadership in science and technology – and networking and information technology (NIT) in particular – is essential to the Nation's global competitiveness and economic prosperity. For example, one study reports that since 1995, the NIT industries have accounted for 25% of the Nation's economic growth, although they represent only 3% of the gross domestic product (GDP).[3] As underscored by several recent high-profile reports and developments,[4] the heightened interest in NIT among policy makers is based on the promise of new market opportunities and technological advances.

However, continuation of America's strong position in developing and adopting new networking and information technology is not assured. Other nations have recognized the value of NIT leadership and are mounting challenges. In this chapter, the PCAST presents highlights from its assessment of global NIT competition. The PCAST concludes that changes in Federal policy and directions for Federal NIT research and development (R&D) investments are needed if America is to maintain its strong position.

THE GLOBAL COMPETITION

Many countries and regions have interests in advancing their competitiveness through NIT. The PCAST focused its assessment on the United States and the countries and regions that PCAST members think may pose the most serious competitive threat to America's position in NIT.

The United States

The United States is the current global leader in NIT, though it faces increasing competitive challenges. A key element of this leadership is the market position of U.S. NIT firms. Many dominate their markets in segments such as microprocessors, operating systems, Internet search, and supercomputers. In 2005, more than a third of the top 50 and almost half of the top 250 global information and communication technology (ICT) firms were U.S.-based.[5]

A second element of America's success has been the power of its commercialization system, which combines a vigorous entrepreneurial culture, a supportive legal (including intellectual property) and regulatory environment, and ready access to capital. The result has been the steady generation of new businesses, many of which have become well-known brand names, that bring NIT innovations rapidly to market.

A third enabler of America's status is its unmatched higher education and research system. Recent rankings of university programs in engineering, technology, and computer science show that the United States holds

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[3] Dale W. Jorgenson and Charles Wessner, editors. 2007. *Enhancing Productivity Growth in the Information Age: Measuring and Sustaining the New Economy.* Washington, D.C.: National Academies Press. Also see Dale W. Jorgenson, Mun S. Ho, and Kevin J. Stiroh. 2005. *Productivity Volume 3: Information Technology and the American Growth Resurgence.* Cambridge, Mass.: MIT Press.

[4] The Administration's American Competitiveness Initiative; several bills in the Congress; the National Academies report *Rising Above the Gathering Storm*, 2007; and PCAST's *Sustaining the Nation's Innovation Ecosystems*, June 2004.

[5] ICT may be considered to be comparable to NIT for the purposes of this report. *OECD Information Technology Outlook 2006.* Paris: Organisation for Economic Co-operation and Development.

17 of the top 20 positions and two-thirds of the top 50.[6] These institutions produce a large fraction of the high-quality research publications in these fields (though the fraction of U.S. publications is declining), as well as the trained, talented engineers and computer and information scientists needed to create and staff organizations within the NIT ecosystem. Since the early days of networking and information technology, a significant portion of research funds in these institutions has been provided by the Federal government.

These three elements – strong NIT firms, a powerful commercialization system, and high-quality education and research institutions – have been critical to America's leadership in NIT, but they do not fully explain it. These elements operate within and depend upon a larger NIT ecosystem that also includes governmental bodies, non-NIT industrial firms, non-profit research organizations, employees, customers, and other elements, which together conduct a wide range of activities necessary for the ecosystem's success. Many of the elements are intricately interrelated with each other and with elements outside the NIT ecosystem through exchanges of knowledge, products, services, funds, and people.

America's favorable global competitive position in networking and information technology is a product of its entire NIT ecosystem; it is currently the NIT leader because that ecosystem is:

Broad – participating in every segment of NIT,

Deep – conducting every type of activity from R&D to sales and service in most segments, and

Strong – at or close to world leadership in the market, in R&D, and in education in virtually all segments.

While the American NIT ecosystem continues to evolve and prosper, other nations and regions are also moving forward, some of them faster than America in some areas and sometimes at an accelerating pace. While no nation or region has yet mounted a successful across-the-board challenge to the dominance of the American NIT ecosystem, several are working assiduously and successfully to put key elements in place and have already achieved leadership in selected areas. The challenges take different forms in different nations or regions.

Today's Major Competitors

Presently, the three strongest country and regional competitors to the United States are Japan, East Asia (South Korea, Taiwan, and Singapore), and the European Union.

Japan

Japan's established commercial strengths lie in electronics and electro-mechanical design and manufacturing and in advanced technology development. These strengths are reflected in its manufacturers' dominant positions, only recently being challenged by South Korean manufacturers, in the full range of consumer electronics, their technological leadership in video and digital photography, and their strong position in computer components and office machinery.

Education is another advantage. Japan's universities are the best in Asia and are attracting a growing number of students from other Asian countries to their graduate programs.

Japan's scientific and technological research has strengthened in the last few decades. The Japanese Earth Simulator, a supercomputer designed for predicting the behavior of the Earth and its atmosphere, was ranked

[6] "Academic Rankings of World Universities by Broad Subject Fields – 2007, Engineering, Technology and Computer Science," Institute of Higher Education, Shanghai Jiao Tong University, available at http://ed.sjtu.edu.cn/ARWU-FIELD2007/ENG.htm.

the fastest in the world from June 2002 to November 2004.[7] In addition, in a ranking based on the number of U.S. patents granted, five of the top 10 companies are Japanese. Companies in Japan receive about the same number of triadic patents – those that have been granted in the United States, Europe, and Japan – as companies based in the United States or Europe.[8]

Laptop Computers and the Global Networking and Information Technology Ecosystem

The American NIT ecosystem, despite its breadth, depth, and strength, is tightly interconnected with and highly reliant on the global NIT ecosystem. The primary routes that American customers' orders for laptop computers bearing American companies' brand names take from the customers' on-line entries to the products' delivery by an express service illustrate that interrelationship.

Usually, customer orders go quickly to factories in China, where about 80 percent of the world's laptop and desktop computers are assembled.[9] Those factories are mostly operated by a number of Taiwanese original design manufacturers (ODMs), which together dominate the manufacture of laptops. The ODMs purchase components that the American companies have selected and contracted for from companies around the world. In some cases, the ODMs assemble most of the components at their Chinese factories. The partially completed laptops are then sent to the American companies' plants located in other countries, where the microprocessors, software, and other key components are inserted; then they are shipped to distribution centers in the United States for packaging with manuals, cords, additional software, and shipment to customers. In other cases, the ODMs completely assemble the components at their Chinese factories, from which the finished laptops are shipped directly to customers.

The companies whose products or services are brought together in the laptop computer divide roughly into three tiers, as shown in Table 1 (page 12). In Tier 1 are, for example, Advanced Micro Devices (AMD), Apple, Intel, and Microsoft, whose value added is derived from the unique intellectual property they control – the basic architecture of a computer, its microprocessor, and its operating system. In Tier 2 are the laptop architects and marketers, such as Apple, Dell, Gateway, and Hewlett-Packard (HP), and designers and manufacturers, such as Quanta. Their value comes from the overall conception and design of the laptop and the management of its manufacturing, marketing, distribution, and service. In Tier 3 are the suppliers of key components of the laptop whose value is derived from their ability to produce high-quality commodity-like components (such as memory modules) at a competitive price.

A significant portion of the intellectual property underlying these products comes from academic research laboratories. For example, the graphics processor that enables a laptop to display high-quality, rapidly moving graphical images incorporates algorithms and hardware developed in American computer science departments with funding from Federal agencies.[10]

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[7] Based on the TOP500 List presented by the Universities of Mannheim and Tennessee and Lawrence Berkeley National Laboratory, available at http://www.top500.org.

[8] National Science Board. *Science and Engineering Indicators 2006.* Arlington, Va.: National Science Foundation.

[9] A detailed description of the global laptop ecosystem can be found in William Foster, Zhang Cheng, Jason Dedrick, and Kenneth L. Kraemer, "Technology and Organizational Factors in the Notebook Industry Supply Chain." CAPS: Center for Strategic Supply Research, 2006. Available at http://pcic.merage.uci.edu/papers/2006/CAPSenglish.pdf.

[10] Based on input from PCAST's Technical Advisory Group for Networking and Information Technology.

East Asia

Following Japan's lead, South Korea, Taiwan, and Singapore have built strong NIT manufacturing industries that, with Japan, now lead the markets for dynamic random access memory (DRAM), portable digital devices, displays, audio and video products, computer peripherals, and other mass-manufactured digital and electronic devices. Firms in these countries manufacture products – some in mainland China – that often arrive in the market under American, European, or Japanese manufacturers' labels.

No Japanese or East Asian company is a leading player in the global software or business services markets, although Japan is taking some initiative through its Information-Technology Promotion Agency to develop and disseminate advanced software engineering practices and innovative software products.[11]

Table 1: Value Added in the Production of a Laptop Computer[12]

Value Added	Example Companies	Locations of Corporate Headquarters[13]
	Tier 1	
Microprocessors	AMD, Intel	United States
Operating systems	Apple, Microsoft	United States
	Tier 2	
Architecture, specification, contracting, marketing, sales, and service	Apple, Dell, Gateway, HP, Lenovo, Toshiba	China, Japan, United States
Design and manufacture	Compal, Quanta	Taiwan
	Tier 3	
Hard disk drives	Hitachi, Seagate	Japan, United States
Optical disk drives	Panasonic, Sony	Japan
Memory chips	Many	Germany, South Korea, Taiwan, United States
Liquid-crystal displays	Many	China, Japan, South Korea, Taiwan
Graphics processors	ATI (owned by AMD), nVIDIA	United States
Power supplies	Many	China
Magnesium cases, keyboards	Many	China

[11] http://www.ipa.go.jp/about/english/index.html.

[12] The example companies and locations of corporate headquarters are listed in alphabetical order within each cell.

[13] Most of the companies have operations, such as research, design, development, and manufacture, in other countries as well. For example, Intel has design and manufacturing facilities in Israel and is building a semiconductor manufacturing plant in China.

European Union

The NIT strengths of the European Union (EU) lie in telecommunications, some segments of the semiconductor market, real-time and enterprise software, and education. The EU research community also has a long history in basic software development, extending from early programming language development to current strengths in software theory. In the 2007 Global Information Technology Report,[14] which evaluates how well countries exploit ICT for economic growth, eight of the top ten countries are European. The U.S. fell from first place in 2005 to seventh place in 2007 based on the criteria used in the assessment.

The EU has set a goal of strengthening its position in ICT. Under the 7th European Framework Programme for Research and Technological Development (2007-2013), ICT is one of ten thematic areas chosen for emphasis in Cooperative R&D, which encourages joint efforts among governments, industry, and academia. ICT is receiving by far the largest portion of the cooperative funds, 9.1 billion euros (over $12 billion in mid-2007 U.S. dollars), almost 30% of the total. Areas of ICT emphasis include nano-electronics, mobile and wireless communications, embedded systems, networked and electronic media, software and electronic services, robotics, photonics, and satellite communications. The 7th Framework Programme is indicative of the priority, organizational effort, and resources that the EU, its member countries, its industries, and its research organizations are devoting to mounting a multiyear challenge to America's global leadership position in NIT.[15]

Emerging Competitors

The challenge to America's NIT leadership posed by two countries in the developing world – India and China – is newer, faster growing, and broader than the challenges arising from the developed world.

In recent years, both India and China[16] have doubled their production of three- and four-year degree holders in engineering, computer science, and information technology. In 2004, India and China graduated about 860,000 engineers, computer scientists, and information technologists – 215,000 in India and 644,100 in China.[17] Of these, only slightly over half received four-year bachelors degrees; the remainder earned two- or three-year technician or associates degrees. In the same year, the United States produced 137,400 bachelor-level graduates in those fields and another 84,900 at the associate-degree level.

However, a recent global labor market study concluded that only 25% of Indian engineers and 10% of Chinese engineers can compete in the global outsourcing market due to "lack of necessary language skills, the low quality of significant portions of the educational system and its limited ability to impart practical skills, and a lack of cultural fit, which can be seen in interpersonal skills and attitudes towards teamwork and flexible working hours."[18] Although the starting salaries of engineers in India and China are a fraction of those in the United States, the salaries of the engineers who can meet the standards of multinational corporations in India and China are increasing more rapidly than the salaries of engineers in the United States because they are in short supply.

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[14] Soumitra Dutta and Irene Mia. 2007. *The Global Information Technology Report 2006-2007.* New York: World Economic Forum and Palgrave Macmillan.

[15] Further information about the 7th Framework Programme is available at http://cordis.europa.eu/fp7/home_en.html.

[16] National Academies. 2007. *Rising Above the Gathering Storm.* Washington, D.C.: National Academies Press, p. 16.

[17] Master of Engineering Management Program, Duke University. *Framing the Engineering Outsourcing Debate: Placing the United States on a Level Playing Field with China and India.* December 2005. Table 1. p. 5.

[18] Diana Farrell, Martha Laboissière, Jaeson Rosenfeld, Sascha Stürze, and Fusayo Umezawa. 2005. "The Emerging Global Labor Market: Part II – The Supply of Offshore Talent in Services – Executive Summary," *McKinsey Global Institute,* June, p. 7.

India

India's principal immediate challenge to America's NIT ecosystem lies in software and business services. The total revenue for India's software and businesses services industries is projected to reach nearly $50 billion in 2008, with well over $36 billion of that in exports. India is reported to be on pace to achieve $60 billion in NIT exports by 2010.[19] Employment in this industry is expected to reach 1.6 million in 2007. Based on the projected 2010 revenue, a shortage of 500,000 staff is anticipated.

A fundamental driver of India's NIT expansion is its selective higher education institutions, notably the Indian Institutes of Technology (IITs), which produce a talented cadre of engineers, mathematicians, and scientists. For many years, this education provided a route to emigration to other countries, usually the United States, for graduate education and subsequent employment.

This influx of Indian engineers has been beneficial to the American NIT ecosystem. Many developers and entrepreneurs in Silicon Valley, for example, were born in India.[20] However, with the growth of software outsourcing and back-office services, there are more opportunities now for expatriates to return and for those just graduating to remain, which may reduce that flow.

China

China's challenge to America's leadership in networking and information technology involves the simultaneous and rapid development of substantial portions of a comprehensive NIT ecosystem. China's current state in most elements of that system is a fraction of the U.S. position, but its growth rates are generally greater than those of the United States. While those growth rates are from small base numbers, China has maintained high economic growth rates even as its economy has reached substantial size, and may be able to sustain high rates in growing its NIT ecosystem as well.

China's overall science and technology ecosystem is developing rapidly. For example:

- China will soon confer a larger number of doctoral degrees annually in science and engineering than the United States.[21]
- R&D spending in China increased at a double-digit rate from 2002 to 2006, exceeding that of Japan in 2006. China's R&D in 2006 was approximately 1.4% of GDP and is on a path to achieve a national goal of 2.5% by 2020.[22]
- China is now the fifth-leading nation as measured by share of the world's scientific publications, and the citation rate of its papers has grown exponentially.[23]
- China's commercialization system is developing rapidly; venture capital investment in China has more than tripled since 2001, although the amount of capital remains low compared to the United States. In 2005, China attracted 48% and India 10% of the venture capital investments made in Asia.[24]

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[19] National Association of Software and Service Companies. *Strategic Review 2007.* The figures are reported for the fiscal year 2008, which ends on March 31, 2008. See also http://www.nasscom.in/Nasscom/templates/NormalPage.aspx?id=51734.

[20] Vivek Wadhwa, AnnaLee Saxenian, Ben Rissing, and Gary Gereffi, "America's New Immigrant Entrepreneurs: Part I," Working Paper, Pratt School of Engineering, Duke University and School of Information, University of California, Berkeley, January 4, 2007.

[21] Cong Cao, Richard P. Suttmeier, and Denis Fred Simon, "China's 15-year Science and Technology Plan," *Physics Today,* December 2006, pp. 38-43.

[22] OECD. 2006. *Science, Technology, and Industry Outlook 2006.* Paris: OECD.

[23] Ping Zhou and Loet Leydesdorff, "The Emergence of China as a Leading Nation in Science," *Research Policy,* Vol. 35, Issue 1, February 2006, pp. 83-104.

[24] Presentation by Dixon Doll at the second meeting of the Committee on Assessing the Impact of Changes in the Information Technology R&D Ecosystem, National Research Council, Mountain View, California, February 23, 2007.

Chinese NIT firms are expanding rapidly, principally by acquiring technologies, brands, distribution, and management abroad. Although its firms do not have a significant place among the top 250 in the NIT industry, China passed the United States to become the world's leading exporter of NIT products in 2004, primarily by attracting foreign firms and third-party manufacturers that are focused on assembly operations.[25]

Chinese NIT industry-sponsored R&D is small. However, international firms such as Cisco, IBM, Microsoft, and Motorola[26] are establishing R&D centers in China that are responsive to their global strategies, and these centers provide a foundation for the development of world-class labs in China.

China's NIT prospects are summarized in a 2006 OECD assessment: "With a sharper focus on research and development, a rising number of graduates in engineering and science both at home and abroad, the surge in private firms now generating over half of the country's GDP, and a growing use of the e-economy, China is set to take a leading role in future IT developments worldwide."[27]

Summary Assessment: Challenges to America's NIT Leadership

America's global leadership in networking and information technology faces substantial, growing, and diverse challenges from both developed and developing nations and regions. Although no single nation or region today can match the overall strength of the American NIT ecosystem, together they constitute a formidable and accelerating challenge to many of its key elements.

IMPROVING AMERICA'S NIT ECOSYSTEM

The PCAST's assessment of the American NIT ecosystem, although generally positive, exposed elements that need to be strengthened. There are also technical areas that are especially rich in opportunity for advancing NIT. Three areas for improving the U.S. NIT ecosystem are:

Education and Training in Networking and Information Technology. People are the fundamental resource of the NIT ecosystem. Their knowledge, talents, creativity, and perseverance ultimately determine its strength. However, these human resources need continual renewal. Such renewal is achieved through an education and training system that recruits, educates, inspires, and helps find and sustain worthwhile, satisfying career paths in the NIT ecosystem for its graduates. Renewal also is achieved by enabling the best and brightest scientists and engineers from around the world to come to the United States to work and contribute to our Nation's NIT ecosystem. The PCAST concluded that this system, in its current form, will be inadequate to provide the number of properly qualified NIT professionals needed for the future. Findings and recommendations about improving education and training are presented in Chapter 2. The PCAST also supports the provisions of the President's American Competitiveness Initiative for reforming immigration policies to increase our Nation's ability to compete for and to retain top science and technology professionals from around the globe.

[25] OECD. 2006. *OECD Information Technology Outlook.* Paris: OECD.

[26] http://newsroom.cisco.com/dlls/global/asiapac/news/2004/pr_09-23.html, http://www.research.ibm.com/beijing/, http://research.microsoft.com/aboutmsr/labs/asia/default.aspx, http://www.motorola.com.cn/en/about/inchina/joint.asp, and Gregory T. Huang, "The World's Hottest Computer Lab: Microsoft's Six-year-old Beijing Lab Has Already Paid Dividends in Speech Recognition, Wireless Multimedia and Graphics," *Technology Review,* June 2004, available at http://www.technologyreview.com/Biztech/13616/.

[27] "Made in China," *OECD Observer,* November 2006.

Structure of the Federal NIT R&D Portfolio and Technology Transfer. NIT R&D takes myriad forms that include single university scientists in a single discipline performing long-time-horizon research with uncertain payoff and large teams of scientists and engineers from diverse fields developing complex products in an industrial laboratory. A diversity of forms is essential, but equally essential is an appropriate balance among them to meet the needs of a vigorous and innovative NIT ecosystem. The PCAST finds that the current mix of types of Federally funded NIT R&D is out of balance, with an excessive emphasis on short-term, incremental research. Findings and recommendations for addressing this imbalance are provided in Chapter 3.

Prioritization of Technical Areas in NIT R&D. Almost all major NIT innovations have originated and been initially exploited in the United States. The domain is still young and full of opportunity, and the United States continues to explore it. Federal investments are both in NIT areas that have long been priorities and in new areas that hold the promise of further improving this country's security, economy, and quality of life. Future directions and Federal priorities for these technologies are discussed in Chapter 4.

Chapter 2

Networking and Information Technology Education and Training

A necessary condition for the success of the American NIT ecosystem is the availability of enough properly qualified NIT professionals, especially the scientists and engineers at the foundation of America's global leadership in NIT. As the competition for that leadership intensifies, the need for such professionals grows. However, the number of people completing NIT education programs and the usefulness of that education fall short of current and projected needs. In this chapter, the PCAST discusses the nature of the need – or demand – for NIT professionals, the shortfall in school enrollments, and the shortcomings in educational programs, and makes recommendations for strengthening these programs.

THE DEMAND FOR NETWORKING AND INFORMATION TECHNOLOGY PROFESSIONALS

Both the long-term projections of the Department of Labor (DOL)[28] and short-term labor market analyses by private organizations indicate a continuing strong demand for qualified NIT professionals, especially those with specialized skills and specific domain and industry experience. This picture is reinforced by surveys and statements of corporate leaders, who virtually uniformly express concern about their inability to hire the number of skilled technologists they need. However, behind these statements is a complex picture.

The domain of networking and information technology covers a broad range of specialties, from computer systems operator to researcher to network administrator to information manager, with a similarly broad range of educational requirements, from an associate to a doctoral degree. The enormous diversity of relevant occupations makes it difficult to assess the demand for and supply of NIT professionals across the board.

However, national labor data show that the overall profile of job demand is rapidly evolving. Since 2000, the demand for certain specialties, notably entry-level programming and database analysis, has shrunk, while demand for others, such as systems design and analysis, business process improvement, and NIT project management, has expanded. By 2005, total NIT employment had rebounded to the levels reached in 2000 at the height of the dot-com boom.[29] However, employment growth leveled off in mid-2006.[30]

According to the latest data from the DOL's Bureau of Labor Statistics (BLS), employment in the computer and mathematical science occupational group in 2004 was 3.2 million and was projected to increase by almost 1 million by 2014.[31] This is a greater percentage increase (31%) than any other major occupational group except health-care support (33%).

Over the decade 2004-2014, the BLS projects increases of 25% for computer scientists, 46% for computer software engineers, 38% for network and computer systems administrators, and 55% for network systems and data communications analysts, making them among the fastest-growing occupations during that period. BLS

[28] Daniel E. Hecker, "Occupational Employment Projections to 2014," *Monthly Labor Review,* DOL, November 2005, pp. 70-101.

[29] Mark Roberts, National Association of Computer Consultant Businesses, January 2006 (quoted in *TechRepublic,* available at http://blogs.techrepublic.com.com/tech-news/?p=322).

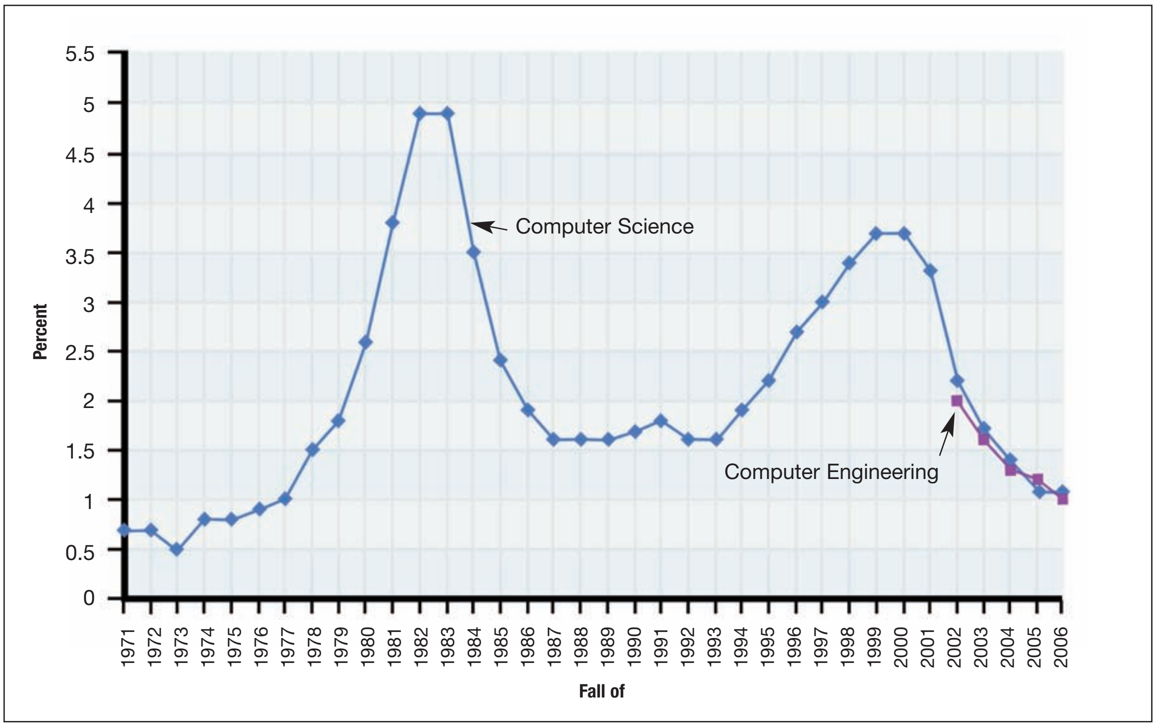
[30] "Shortage of IT Talent Hampers Growth; Overall IT Employment Continues Move Sideways," National Association of Computer Consultant Businesses, April 10, 2007.

[31] Hecker, op. cit.

surveys also show that in 2004 average salaries in computer and mathematical science were higher than those in all other occupational groups except the management and the legal groups.[32]

From a U.S. perspective, the demand for an employee can be satisfied in three different ways: by filling it with a qualified person of U.S. nationality in the United States, by "importing" the person to fill a job associated with a U.S.-based company, and by "exporting" the job to a nation where employees are available. From an employer's perspective, these options may be equally feasible, with the choice based primarily on comparative effectiveness and cost. From the perspective of the Federal government, the preference is that high-quality, well-paid jobs are filled by U.S. citizens, permanent residents, or immigrants who remain in America. Thus, there not only must be an adequate supply of well-trained professionals, but they must be able to perform at the high level of effectiveness that is commensurate with their relatively high compensation. Openings that cannot be filled effectively and economically in the United States may well be outsourced abroad.

Figure 1: Computer Science and Computer Engineering Listed as Probable Majors Among Incoming First-Year College Students in the United States

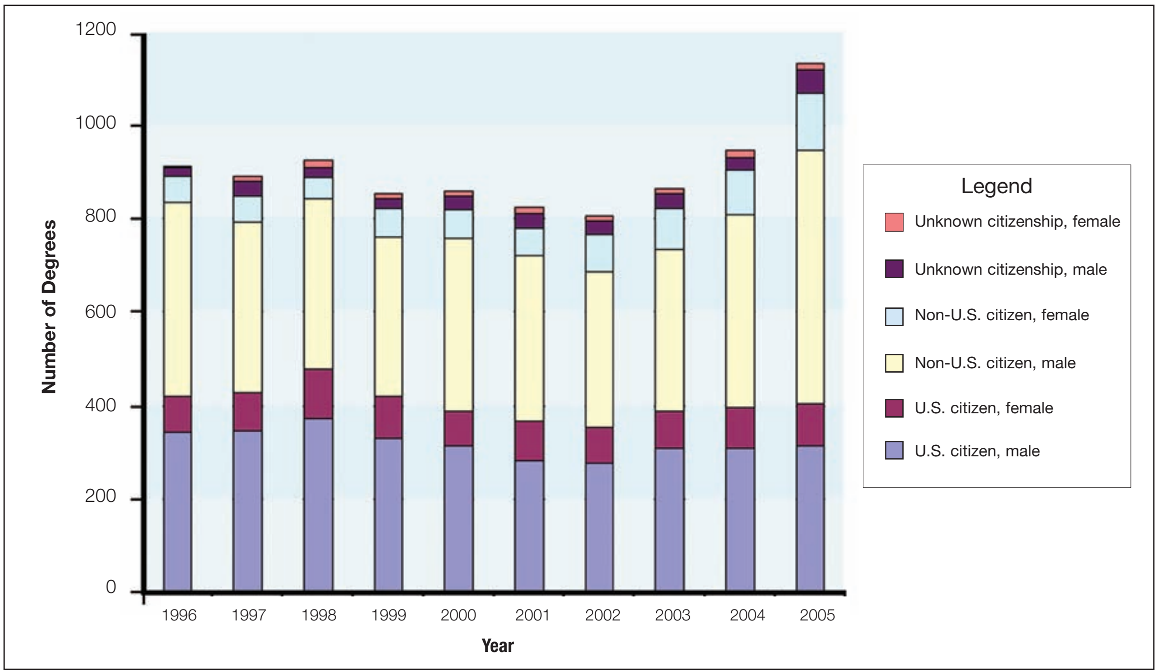


The portion of first-year college students listing computer science as their probable major has declined from almost 4% in 2000 to 1%, which is the lowest rate for computer science since 1977. (Source: Computing Research Association, based on data from the University of California, Los Angeles[33])

[32] Fatemeh Hajiha, "Employment and Wages by Major Occupational Group and Industry," Bureau of Labor Statistics, November 2005, available at http://www.bls.gov/oes/2004/may/major.pdf.

[33] Based on a figure published in the *CRA Bulletin,* February 8, 2006, Jay Vegso, available at http://www.cra.org/wp/index.php?p=75. The data source was the Cooperative Institutional Research Program (CIRP) annual Freshman Survey conducted by the Higher Education Research Institute, Graduate School of Education and Information Studies, University of California, Los Angeles.

Figure 2: Computer Science Doctorates Awarded in the United States



The recent increase in the number of U.S. computer science doctorates awarded is almost entirely due to increases in the numbers awarded to non-U.S. students. The number awarded to U.S. citizens remained fairly steady at around 400 per year from 1996 through 2005. (Source: National Science Foundation[34])

Finding: Over the coming decade, U.S. demand for networking and information technology professionals, with the exception of some readily outsourced or technologically outdated jobs, is likely to grow more rapidly than for most other employment categories. The new job openings are expected to offer higher-than-average salaries and benefits.

THE SUPPLY OF NETWORKING AND INFORMATION TECHNOLOGY PROFESSIONALS

As on the demand side, assessment of the supply of NIT professionals benefits from a more nuanced analysis than a summary statement that the number of NIT graduates over all is growing. The same variety of fields and educational programs is present, with increases or decreases similar to those on the demand side in people preparing to enter different specialties.

NIT professionals are educated in a wide range of academic departments, some of which may appear to have no direct relation to NIT. One must look beyond computer science and engineering or even information science and information systems programs to understand the sources of NIT professionals. Nevertheless, considering only computer science and engineering programs, the bachelor's and master's levels are the principal sources of computer and networking specialists, and the doctoral level produces the faculty for those programs and researchers for NIT laboratories in industry and government.

[34] National Science Foundation (NSF), Division of Science Resources Statistics (SRS), "Science and Engineering Doctorate Awards: 2005," available at http://www.nsf.gov/statistics/nsf07305/.

Indicators of the Supply of NIT Professionals

- The number of new NIT graduates has grown steadily, even after the Y2K transition and dot-com crash. According to the National Science Foundation (NSF), 57,400 bachelor's degrees were awarded in computer science in 2004, up from 37,400 in 2000.[35]
- However, the Computing Research Association survey of Ph.D.-granting computer science departments – about 30% of the computer science departments covered by the NSF data – shows that the number of new computer science majors in these institutions dropped by half between 2000 and 2006 (from 15,960 to 7,800), and the number of bachelor's degrees granted by them fell about 39% between academic years 2001-2 and 2005-6.[36]
- The percentage of women among the graduates of baccalaureate mathematics and computer science programs is decreasing, in contrast to women's increasing representation in other science and engineering programs. According to NSF, women represented about 40% of bachelor's recipients in mathematics and computer science in 1985, but only 29% in 2004. Among all major fields, only engineering had a lower percentage of women (21%).[37] Underrepresented minorities were awarded about 19% of computer science degrees in 2004, little changed from the 18% in 1995.[38]
- According to NSF, the total number of Ph.D. recipients in computer science reached a peak of almost 1,000 in 1995, then declined to 807 in 2002, but rebounded to 1,136 in 2005, the latest year for which NSF data are available. Of the 2005 total, 225 were women – the highest number ever, but still only 20%.[39]

While the overall number of NIT specialists continues to grow, the number of students entering the domain through computer science and computer engineering programs has recently been declining. Contributing factors are weak K-12 preparation in science and mathematics, which reduces the size of the qualified applicant pool,[40] and students' and parents' unfavorable – and PCAST thinks misguided – views about computer science and engineering, which divert potential qualified applicants to other domains. Prospective students view the dot-com bust and offshoring as having reduced the number of jobs and the salaries for computer science graduates and have been swayed by the stereotype of computer professionals as socially unskilled. Rarely is the breadth, relevance, and excitement of the domain conveyed in ways that attract a wide range of students, particularly women and minorities, who are underrepresented among computer science and engineering graduates.

In computer science doctoral programs, a shortfall in American enrollees has been offset in the past by international students, especially from India and China. Many of these students, often their country's best

[35] NSF, SRS Science and Engineering Degrees: 1966-2004, "Table 34. Computer science degrees awarded, by degree level and sex of recipient: 1966-2004," available at http://www.nsf.gov/statistics/nsf07307/pdf/tab34.pdf.

[36] *CRA Bulletin,* March 8, 2007, "Drop in Bachelor's Degrees Granted," available at http://www.cra.org/wp/index.php?p=105.

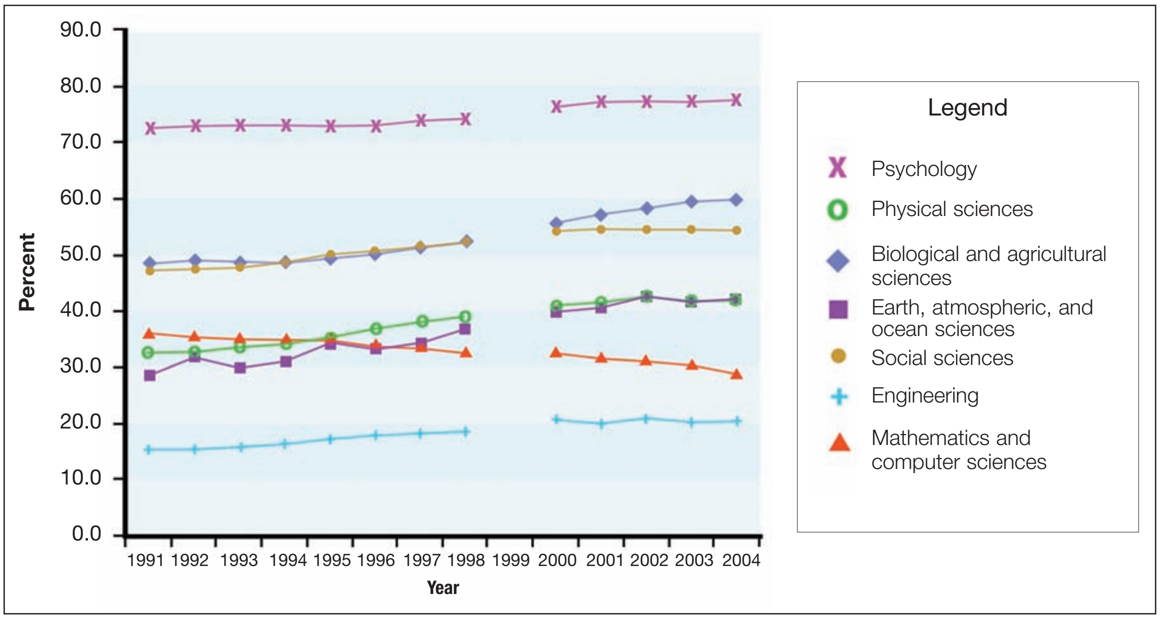
[37] NSF, SRS Science and Engineering Degrees: 1966-2004, "Table 11. Women as a percentage of all bachelor's recipients, by major field group: 1966-2004," available at http://www.nsf.gov/statistics/nsf07307/pdf/tab11.pdf.

[38] NSF, SRS Science and Engineering Degrees: 1966-2004, "Table C-7. Racial/ethnic distribution of S&E bachelor's degrees awarded to U.S. citizens and permanent residents, by field: 1995-2004," available at http://www.nsf.gov/statistics/wmpd/pdf/tabc-7.pdf.

[39] NSF, SRS Science and Engineering Degrees: 1966-2005, "Table 3. Doctorates awarded, by sex, citizenship status, and major field of study of recipient: 1966-2005," available at http://www.nsf.gov/statistics/nsf07305/pdf/tab3.pdf.

[40] For discussion of K-12 science and mathematics education and the low graduation rates at the bachelor's level in science, engineering, technology, and mathematics of incoming students intending to major in these areas, see PCAST's report *Sustaining the Nation's Innovation Ecosystems,* June 2004.

Figure 3: Women as a Percentage of Bachelor's Recipients, by Field



In contrast to other science and engineering fields, in computer science a relatively low and declining portion of bachelor's degrees are awarded to women. (Source: Computing Research Association, based on NSF data[41])

and brightest, have remained in the United States and contributed to U.S. industry and academia, and represented a net benefit to the U.S. NIT ecosystem. At the same time as some lower-level jobs have been exported to other countries, the United States has imported highly talented individuals to populate top-level positions in its NIT ecosystem.

This supply may decline in the face of increased difficulties of obtaining student and work visas and the heightened attractiveness in their home countries of academic and corporate jobs, the climate for entrepreneurial activities, and the standards of living. In addition, some who might have come to the United States in the past now stay in their home countries for graduate education, especially as the quality of that education improves. These trends along with failings and shortfalls in U.S. science and mathematics education and negative stereotypes may lead to shortages of doctoral-level NIT professionals that put U.S. intellectual and commercial leadership at risk.

Finding: Although the overall supply of networking and information technology specialists is expected to grow in response to the growth in total demand, at current rates of enrollment and graduation, shortfalls in the numbers of highly qualified computer scientists and engineers graduated at the undergraduate and doctoral levels are likely. Women and other underrepresented groups will constitute a declining proportion of the new graduates.

However, it will not be enough simply to increase the supply of NIT professionals if their education is not brought into closer conformance with the needs of their current and future employers.

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[41] NSF, SRS, Science and Engineering Statistics. S&E Degrees Series. Women, Minorities, and Persons with Disabilities in Science and Engineering, "Table C-5. Bachelor's degrees, by field and sex: 1995-2004," available at http://www.nsf.gov/statistics/wmpd/pdf/tabc-5.pdf. NOTE: Data for 1999 are missing.

THE EDUCATION OF NETWORKING AND INFORMATION TECHNOLOGY PROFESSIONALS

While the domain of networking and information technology has evolved rapidly, as have the institutions that create, deploy, and use NIT, the education of new generations of NIT professionals has not kept pace. NIT curricula in general, and computer science curricula in particular, are lagging behind industrial practice and employer needs. According to observers from academia, professional societies,[42] and industry, NIT curricula, especially in computer science, need to:

- Reflect the fact that computing touches all aspects of society
- Provide sufficient early exposure to applications of NIT and their impact on the economy and society generally
- Provide opportunities to integrate NIT with other domains and disciplines
- Train students in the multidisciplinary teamwork needed to solve complex, real-world problems
- Be more responsive to the varied backgrounds and perceptions of today's diverse student base
- Be at the state of the art in what is taught, how it is taught, and in the technological infrastructure available to students
- Focus more on broader issues of theory and practice that address *why* and less on the mechanics of *how* tasks are performed
- Codify and teach higher-level skills, such as systems architecture, analysis, and design, and project management, so that graduates can enter the workforce at higher levels, as lower-level tasks are automated or outsourced

Finding: Networking and information technology curricula in general, and computer science curricula specifically, do not adequately meet employer and student needs.

Because the domain of networking and information technology continues to advance, NIT curricula must be regularly revised and graduates must continue to update and expand their knowledge and skills throughout their careers. Unless every level of its NIT workforce, from recent graduate to experienced professional, remains current, the United States risks losing advantage to more knowledgeable and skilled competitors elsewhere.

ENSURING AN ADEQUATE SUPPLY OF WELL-EDUCATED NIT PROFESSIONALS

The Federal government, under the leadership of the Office of Science and Technology Policy and NIT R&D agencies, and with the active engagement of academia and industry, should undertake a nationwide effort to strengthen NIT education and training programs, to publicize the need for NIT professionals of all types, and to identify qualifications in demand.

Special attention should be paid to programs that educate future generations of workers involved in research and development, whose innovations and leadership will be critical to America's competitiveness in NIT industries.

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[42] For example, "Computing Curricula 2005," the Joint Task Force for Computing Curricula 2005, a cooperative project of the Association for Computing Machinery, the Association for Information Systems, and the IEEE Computer Society. September 30, 2005.

Recommendation: To provide a solid basis for subsequent action, the NITRD Subcommittee should charge the NITRD National Coordination Office to commission one or more fast-track studies on the current state of and future requirements for networking and information technology undergraduate and graduate education.

Drawing upon the knowledge of leaders from academia, professional societies, industry, and government, the project should address:

- The expected *supply of and demand for* NIT professionals over the coming decade, with a focus on women and other underrepresented groups
- The current state of and future requirements for *curricula* in NIT fields, with special attention to computer science and to the integration of computer science with fields that apply computer science
- Public and student *perceptions* of NIT fields and what might be done to improve those perceptions
- Comparisons with other nations

While this work is underway, the PCAST encourages NIT academic departments, Federal agencies, and professional societies to continue to improve curricula and student recruitment. The PCAST identified a number of beneficial efforts, but they are not sufficient to meet the full range of needs. Moreover, greater national visibility and improved coordination and integration of efforts would accelerate progress.

The full range of government activities in support of NIT education should not be determined until the study is finished. However, in the PCAST's view, the supply of NIT professionals with master's and doctoral degrees is critical both to education and to R&D, and there are reasonable steps that can be taken before the study is completed.

Recommendation: To help meet national needs for personnel with advanced degrees in networking and information technology fields, the Federal government should:

- **Increase the number of multiyear fellowships for graduate study by American citizens in NIT fields each year, with the target number and fields of such fellowships informed by needs identified in sources such as the NIT education study**
- **Streamline the process for obtaining visas for non-U.S. students admitted to accredited graduate degree programs in NIT subjects**
- **Make it routine for foreign nationals who have obtained advanced degrees in NIT subjects at accredited U.S. universities to be permitted to work and gain citizenship in the United States by easing the visa and Green Card processes for them**
- **Simplify the visa process for international NIT R&D experts who visit the United States on a regular or a frequent basis for professional purposes**

Chapter 3

Profile of Federal Networking and Information Technology Research and Development

Federally funded NIT R&D has been a powerful stimulus to the NIT ecosystem. However, as the domain of networking and information technology has grown in capability and complexity and has increased its direct impact throughout society, the character of the NIT R&D questions that are critical to further progress have markedly changed. In response, the Federally funded NIT R&D portfolio must also change. In this chapter, PCAST examines and makes recommendations about the evolving nature of NIT, the implications for Federal NIT R&D funding programs and for academic NIT R&D, and the processes for technology transition.

THE EVOLVING NATURE OF NETWORKING AND INFORMATION TECHNOLOGY R&D

Historically, much of Federal NIT R&D funding has gone to individual researchers and small single-discipline groups for shorter-term projects. R&D of that form has been the source of many advances that support agency missions and national priorities, and it must continue as a Federal priority.

However, the number, scope, and impact of applications that rely on networking and information technology have grown, and the nature of the NIT capabilities demanded by those applications has expanded. Computers, networks, software, and the demands placed on them today are larger in scale, more complicated, more integrated – and more essential.[43] (This mirrors the evolution of research challenges in the sciences generally.) Therefore, the small, single-discipline, short-term, Federally funded NIT R&D projects, no matter how well conceived or conducted, cannot by themselves address the complicated, long-time-horizon, multidisciplinary issues that arise from the new NIT capabilities and applications.

To address those issues – the most critical challenge for the NITRD Program in PCAST's view – Federal agencies, as well as universities and industry, must expand the ways in which NIT R&D is funded and conducted. The R&D will need to include more investigations that are long-term rather than short-term; large in scope and scale instead of focused and small; conducted by multidisciplinary teams that work together for many years and not just by single-discipline researchers or small groups; and/or visionary and innovative rather than solid but incremental. These changes are likely to increase the level of risk in Federal agency NIT R&D portfolios, but have the potential of significant payoffs.

The PITAC's 1999 report *Information Technology Research: Investing in Our Future* also addressed the structure of the Federal NIT R&D portfolio. It recommended funding projects of larger scope and duration, the establishment of large centers for "Expeditions to the 21st Century" that would explore future information technologies, and the creation of "Enabling Technology Centers" to conduct research on the application of IT to particular problems of national importance. In response, for five years NSF funded medium- and large-size grants in its Information Technology Research program (which ended in 2004) and the Department of Energy's Office of Science started its Scientific Discovery through Advanced Computing program. However, in contrast to the growing need, the aggregate Federal response to these recommendations has been inadequate.[44]

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[43] These attributes are evident in the technological priorities described in Chapter 4, such as an increased emphasis on NIT systems connected with the physical world.

[44] The Appendix provides further discussion of Federal government responses to the 1999 PITAC report.

Finding: The Federal networking and information technology R&D portfolio is currently imbalanced in favor of low-risk, small-scale, and/or short-term efforts. The number of large-scale, multidisciplinary activities with long time horizons is limited. Few projects, whether small or large, are visionary.

Finding: New ways are needed to stimulate, identify, and fund pioneering networking and information technology R&D that falls outside the scope of conventional funding programs.

Recommendation: Federal agencies should rebalance their networking and information technology R&D funding portfolios by increasing: (1) support for important networking and information technology problems that require larger-scale, longer-term, multidisciplinary R&D and using existing or new mechanisms to address those problems and (2) emphasis on innovative and therefore higher-risk but potentially higher-payoff explorations.

The Office of Science and Technology Policy should oversee the development of a list of important Federal and national problems that require NIT R&D, especially ones that are large-scale, multidisciplinary, and require long-term investments or innovative ideas. These problems may be found both in agencies currently involved in NIT R&D (including units of these agencies that do not have NIT R&D programs) and in agencies that do not have NIT R&D portfolios. Once such problems are identified, the NITRD Program should develop and implement plans to conduct NIT R&D to address them and to deploy the R&D results.

It is likely that new mechanisms will be needed, although existing mechanisms for identifying, planning, budgeting, funding, and managing projects should be used when possible. Mechanisms that work well for smaller projects may not scale. Mechanisms for solely government-funded projects may need to be augmented for projects that require academic or industry support. Previous attempts to let Federal program managers exercise discretion in encouraging, funding, and supporting more innovative research, whatever its size, have largely been unsuccessful, and new approaches should be pursued. The views of the NIT R&D community should be solicited periodically to aid in the development and modification of funding portfolios and processes.

ACADEMIC NETWORKING AND INFORMATION TECHNOLOGY R&D

The Government’s policies and practices for funding NIT R&D affect and are affected by universities’ single-discipline-based organizational structures and reward systems. Too few academic researchers interact or collaborate with researchers in other disciplines. As a result, too few are able to respond to solicitations for multidisciplinary research from Federal agencies. The rare researcher-initiated proposals for multidisciplinary research generally involve several investigators, are more difficult to prepare, and have larger budgets. On the agency side, the review is difficult to manage: multidisciplinary peer review poses challenges and each project requires a larger percentage of the funding pool, which is often hard to justify. The disciplinary basis of publication practices and of career paths within academia further reinforces the status quo. Thus, there are numerous roadblocks to increasing multidisciplinary research within academia.

Finding: Universities continue to miss opportunities for research in important networking and information technology fields and applications because their organizational structures and incentive systems encourage and reward work by small groups within traditional disciplines.

Several universities have changed their organizations to facilitate their pursuit of new research directions. The Center for Information Technology Research in the Interest of Society at four campuses of the University of California, the Scientific Computing and Imaging Institute at the University of Utah, and the Intelligent Systems Center at the University of Missouri, Rolla[45] can serve as models for how to take advantage of such new opportunities.

The characteristics of the Federal NIT R&D portfolio add pressures and inefficiencies to academic research. The small budgets and short-term nature of traditional research projects means that researchers prepare more proposals more frequently, possibly to more agencies, and more often risk losing support, especially in a climate in which over 80% of proposals typically are not funded. This leaves researchers less time to focus on visionary ideas or to become involved in developing larger research agendas. When creative ideas are presented, they may not be explained well because they are still in a formative state and they may not be understood or favored by program managers or in peer review. The result is often a low ranking and no funding.

Increasing the emphasis on multidisciplinary research in challenging, nationally important problems would be likely to lead to an increase in the number of students and future researchers. As discussed in Chapter 2, there are fewer students in computer and information science and engineering, and it is increasingly difficult to attract high-school students to the field, which many view as narrow and technical. By increasing the relevance of academic research and teaching through an emphasis on multidisciplinary research, NIT programs would be in a position to attract more, and more diverse, students and to enable them to work in teams on challenging problems relevant to the future.

Recommendation: The Director of the Office of Science and Technology Policy should call on senior officials from Federal agencies with large academic networking and information technology R&D budgets to meet with senior officials from the Nation's major research universities to address how better to conduct large-scale, long-term, multidisciplinary academic research in the development and application of networking and information technology important to the Nation.

The outcomes of these meetings should include specific actions by the Federal agencies and the universities and measurement of progress and the development of metrics for large-scale, long-term, multidisciplinary NIT R&D. Individual universities should plan and implement responses to this call for change, perhaps by creating pilot efforts that contribute to finding effective solutions.

To achieve lasting change, the Federal agencies and the universities should address their discipline-based organizational structures in parallel. Universities should adjust their promotion and tenure policies and practices to better prepare and reward multidisciplinary researchers. Federal agencies should revise their organizations to better support long-term, large-scale, multidisciplinary research, which will provide incentives for universities to change.

[45] http://www.citris-uc.org, http://www.sci.utah.edu, and http://www.isc.umr.edu/.

TRANSITIONING NETWORKING AND INFORMATION TECHNOLOGY R&D RESULTS TO THE MARKETPLACE

The ability to transition ideas from the Nation's R&D institutions to the marketplace has been a key strength of America's science and technology base. Technology transfer is likely to have greater impact on U.S. competitiveness in the future because at a national scale it is not amenable to straightforward replication. By strengthening the mechanisms for transitioning research results into useful products and processes, the Nation will solidify this competitive advantage.

The path from research to use is rarely a straight line. Rather, complex interactions are in play. Some researchers conduct fundamental research solely for its own sake, for which they or others find useful application only at some later (sometimes much later) time. But researchers are also motivated to help solve real-world problems through their conduct of fundamental research.[46] In all successful instances of technology transfer, there are likely to be numerous improvements made to the original ideas. Whatever the motive for the research, sometimes its results never make it to the market, even when they would be beneficial.

The relationship among academia, government, and industry in the conduct of research has evolved. In recent times, with the decline of basic research in industrial settings, it has largely taken the form of a division of labor: long-term, basic, pre-competitive R&D tends to be conducted largely by government-funded researchers, usually in universities, and short-term R&D and product development are largely the domain of industrial laboratories.

Federal funding of industrial NIT R&D can benefit both industry and the Government. While Federal agencies invest principally to develop capabilities to meet their mission needs, industry views Federal funding of R&D differently. First, Federal funding can open new market opportunities. The Government is often willing to pay for leading-edge capabilities, but a firm's nongovernmental customers may currently, or soon will have, similar needs, so it is likely that a commercial market will develop for the new capabilities. Second, Federal funding can reduce risk through demonstrations that an idea has value and by developing it to sufficient maturity that it can be brought to market. Then a firm can add its own intellectual property, incorporate the results in its product line, and realize a better return on its investment. This transfer of Federally funded NIT R&D to the marketplace also provides a return on the investment of U.S taxpayers. The Bayh-Dole Act of 1980 helped to create a lasting favorable environment for the transfer of government-funded R&D results to the private sector for commercialization.[47]

Over all, technology transfer has worked well in networking and information technology. The results are visible today in a wide range of products, including desktops and laptops, mobile devices, file servers, the Internet, and graphical user interfaces.[48]

High-end computing (HEC), considered in Chapter 4, is another example. While the Government has for decades been the primary customer of high-end computing systems and the modeling and simulation done

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[46] Donald E. Stokes, 1997. *Pasteur's Quadrant: Basic Science and Technological Innovation*. Washington, D.C.: Brookings Institution.

[47] A discussion of the Bayh-Dole Act and technology transfer of Federally funded R&D generally can be found in the PCAST's report *Technology Transfer of Federally Funded R&D*, May 2003.

[48] Computer Science and Telecommunications Board. 2003. *Innovation in Information Technology.* Washington, D.C.: National Academies Press.

on those systems, U.S. industry is increasingly reaping competitive advantage from its own HEC-based modeling and simulation. In addition, capabilities developed for HEC systems are increasingly found in mass-market products; these include multicore processors and parallel processing systems that increase speed and reduce power requirements. Other recent examples are in the areas of networking and NIT systems connected with the physical world, which are also discussed in Chapter 4.

Finding: The Federally funded networking and information technology R&D that supports agency missions also serves as a key source of innovation to maintain and advance U.S. networking and information technology industry leadership.

Numerous well-meaning attempts have been made by all sectors to improve the flow of information about new research ideas and results to industry and, through them, into products and services. There are known roadblocks to informing industry about research ideas and results, however, such as intellectual property rights and security concerns. Even when they find out about potentially useful ideas, some companies will not pursue them, because of a lack of motivation or capability.

Despite numerous NIT transition successes, some promising ideas were not successfully transitioned into commercial products. Understanding the reasons for the success – or failure – of current or past technology transition efforts can help increase future success rates.

Recommendation: The NITRD agencies should use, to the fullest extent practicable, available authorities and resources to facilitate the transfer of research results into practical application and commercial products.

The Focus Center Research Program

The Focus Center Research Program (FCRP) is jointly funded by semiconductor and semiconductor supplier industries and the Department of Defense to advance semiconductor chip technologies. The FCRP supports 200 research professors and 400 graduate students at 38 universities organized into five centers. Technology transfer mechanisms include program reviews, technical briefings at sponsor sites, workshops, and an Internet presence. Industry participants assign staff to the centers for the purpose of optimizing the transfer of new knowledge to companies. The FCRP facilitates the recruitment of students performing the research – viewed by some sponsors as the most effective method of technology transfer.

Through R&D, the FCRP is tackling the problem of power conservation in semiconductor designs (e.g., by reducing the amount of power needed per instruction). Results flow directly into the U.S. semiconductor industry to improve performance and enable new products that meet stringent military requirements and benefit the civilian economy. Chips that can operate for years if not decades in devices such as sensors will be useful in both war zones and other dangerous or remote locations. The FCRP represents the type of large-scale, long-term, multidisciplinary R&D addressing potentially high-payoff, but currently high-risk, challenges that should have a larger presence in the NIT R&D portfolio.

The Federal government can also facilitate technology transfer through improved communications. Approaches include inviting, whenever possible, industry representatives to meetings at which NIT researchers share their results and convening meetings of university researchers, industry representatives, and government managers to identify NIT problems and R&D needs and help formulate R&D plans. Improving access to publicly available research results would also encourage their innovative use.

THE ROLE OF STANDARDS IN NETWORKING AND INFORMATION TECHNOLOGY R&D

The definition and adoption of key standards have been important facilitators of progress in every field of NIT. The establishment of standards was a critical enabler of the rapid growth of the personal computer, the World Wide Web, and digital media, for example.

The adoption of standards can affect the competitive position of corporations and nations. Extended competition among standards can balkanize markets and slow the adoption of beneficial technologies, while widespread agreement on standards can facilitate such technologies' entry into use. The PCAST supports the continued partnership between Federal NIT R&D agencies and U.S. NIT industries in working with international standards organizations to maintain America's strong position as a leader in setting NIT standards.

Chapter 4

Technical Priorities for Networking and Information Technology Research and Development

Chapter 3 focused on the funding profile of Federal networking and information technology R&D and on transitioning NIT R&D results to industry. This chapter addresses the NIT R&D agenda. Federal NIT R&D priorities must respond to evolving agency, interagency, and national needs and requirements. But they should also reflect the areas that must be pursued to sustain NIT leadership in the long term.

The PCAST concludes that eight areas deserve priority by the Federal government: NIT Systems Connected with the Physical World; Software; Data, Data Stores, and Data Streams; Networking; High-End Computing; Cyber Security and Information Assurance; Human-Computer Interaction; and NIT and the Social Sciences. As new funding becomes available, the first four areas should receive disproportionately larger funding increases because they address issues for which progress will have both the greatest effect on important applications and the highest leverage in advancing networking and information technology capabilities.

NIT SYSTEMS CONNECTED WITH THE PHYSICAL WORLD

NIT systems connected with the physical world – also called embedded, engineered, or cyber-physical systems – are essential to the effective operation of U.S. defense and intelligence systems and critical infrastructures (e.g., air-traffic-control, power-grid, and water-supply systems). Cyber-physical systems are also at the core of human-scale structures such as vehicles and clinical and home health-care devices as well as large-scale civilian applications such as environmental monitoring, industrial process control, and ground transportation management. These NIT systems, in which computing and networking are deeply integrated into other engineered systems, are connected to the physical world through sensors and actuators to perform crucial monitoring and control functions safely and dependably.

Forms of cyber-physical systems are already in widespread use across civil society as well as in national security. But growing demand for new capabilities and applications will require significant technical advances in the NIT underpinnings of these emerging classes of systems.

Such systems can be difficult and costly to design, build, test, and maintain. They often involve the intricate integration of myriad networked software and hardware components, including multiple subsystems. In monitoring and controlling the functioning of complex, fast-acting physical systems (such as medical devices, weapons systems, manufacturing processes, and power-distribution facilities), they must operate reliably in real time under strict constraints on computing, memory, power, speed, weight, and cost. Moreover, most uses of cyber-physical systems are safety-critical: they must continue to function even when under attack or stress.

The uses for these systems are growing dramatically, and economic competition for markets will intensify over the next decade. The European Union's (EU) Advanced Research and Technology for Embedded Intelligence and Systems (ARTEMIS) program, funded by a public-private investment of 5.4 billion euros (over $7 billion in mid-2007 dollars) between 2007 and 2013, is pursuing R&D to achieve "world leadership in intelligent electronic systems" by 2016.[49] Individual countries in Europe as well as Asia are investing in the development of advanced capabilities for embedded systems.

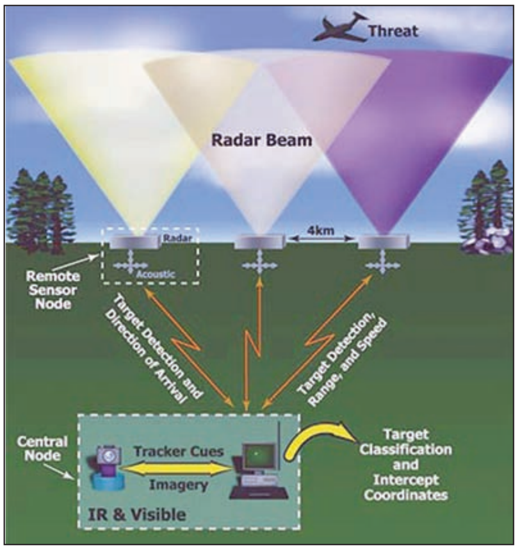
[49] More information about ARTEMIS is at http://www.artemis-office.org/DotNetNuke/Home/tabid/36/Default.aspx.

Finding: NIT systems connected with the physical world are now a national priority for Federal R&D. Improved methods are needed for the efficient development of these systems. These methods must assure high levels of reliability, safety, security, and usability.

Among the goals of a program to improve development methods should be:

- Establishing a scientific basis, a codified knowledge base, and shared principles for designing, building, and operating NIT systems connected with the physical world
- Synthesizing knowledge from the physical sciences, mathematics, engineering, biological sciences, computer science, and other fields to model and simulate such systems in their full complexity and dynamics, including the interactions among potentially many dynamic systems and components in uncertain environments
- Developing a modern NIT systems technology framework to support the real-time computational control requirements of complex, networked, engineered physical systems
- Establishing rigorous, systematic, scalable, and repeatable design, development, verification, and validation methods, particularly to integrate design and certification and thereby accelerate the approval process and reduce the cost of including new NIT-based capabilities in products for public use
- Building a variety of research testbeds that can be used to test, refine, validate, and approve system designs and development methods
- Developing, documenting, and disseminating research-based standards that are integrated throughout the R&D process to achieve best practices for designing systems cost-effectively to function dependably in their environment, with the necessary assurances of reliability, safety, security, and usability

Figure 4: Sensor Field for Threat Detection



This proposed system would detect airborne border crossings through a network of sensors connected to a computer that analyzes the sensor data to classify and locate the intruder. (Figure courtesy of The MITRE Corporation[50])

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[50] Weiqun Shi, Ronald Fante, John Yoder, and Gregory Crawford, “An Eye on the Sky: Detecting and Identifying Airborne Threats with Netted Sensors,” *The Edge*, MITRE Publications, Spring 2006. Vol. 10, No. 1. See also http://www.mitre.org/news/events/tech06/briefings/1406.pdf.

Recommendation: The NITRD Subcommittee should develop and implement a Federal Plan for coordinated multiagency R&D in high-confidence NIT systems connected with the physical world to maximize the effectiveness of Federal investments and help ensure future U.S. competitiveness in these technologies.

Federal R&D agencies should strengthen existing programs or create new ones that cross disciplinary boundaries to accelerate work in this area. The agencies should also place greater priority on devising mechanisms that enable industry and universities to collaborate on pre-competitive research in these systems.

SOFTWARE

The previous section describes one type of system whose software complexity presents difficult technical challenges. However, the complexity of software over all is increasing, as ever-larger systems with many more software components undertaking more complex tasks are built. For example, the percentage of aircraft functionality enabled by software has grown from 10 percent in the 1960s to over 80 percent today.[51]

In one sense, today's wide range of applications dependent on complex software – from integrated avionics, to wireless services and Web search engines, to global financial networks – marks a significant achievement of NIT R&D and the NIT industry. The development of systems dependent on complex software is benefiting from advances in technologies that permit flexible re-use and evolution of software, including modular and object-oriented programming languages.

In another sense, though, software remains NIT's greatest weakness. Although reliable and robust software is central to activities throughout society, much software is brittle, full of bugs and flaws. Software development remains a labor-intensive process in which delays and cost overruns are common, and responding to installed software's errors, anomalies, vulnerabilities, and lack of interoperability is costly to organizations throughout the U.S. economy.[52]

The PCAST strongly agrees with the PITAC's conclusions in its 1999 report *Information Technology Research: Investing in Our Future* – the science of software development must be a focus of Federal NIT R&D. As software's complexity continues to rise, today's design, development, and management problems will become intractable unless fundamental breakthroughs are made in the science and technology of software design and development.

Finding: Software is a critical enabler of America's security, economy, and quality of life and, therefore, is a national priority. However, software presents formidable technical challenges from the foundational to the application level. Success in addressing these challenges will strengthen U.S. competitiveness and NIT leadership.

Although incremental improvements in current practice will continue, the PCAST concludes that fundamental long-term R&D is needed to eliminate conceptual and technical barriers to a next-generation science and practice of software design and development. The goals of the R&D should be to develop foundational principles for software design; formalized science-based software architectures and software design methods; programming languages, tools and practices for modeling, designing, developing, testing, and validating

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[51] GAO. "Defense Acquisitions: Stronger Management Practices Are Needed to Improve DoD's Software-Intensive Weapon Acquisition," March 2004. http://www.gao.gov/new.items/d04393.pdf.

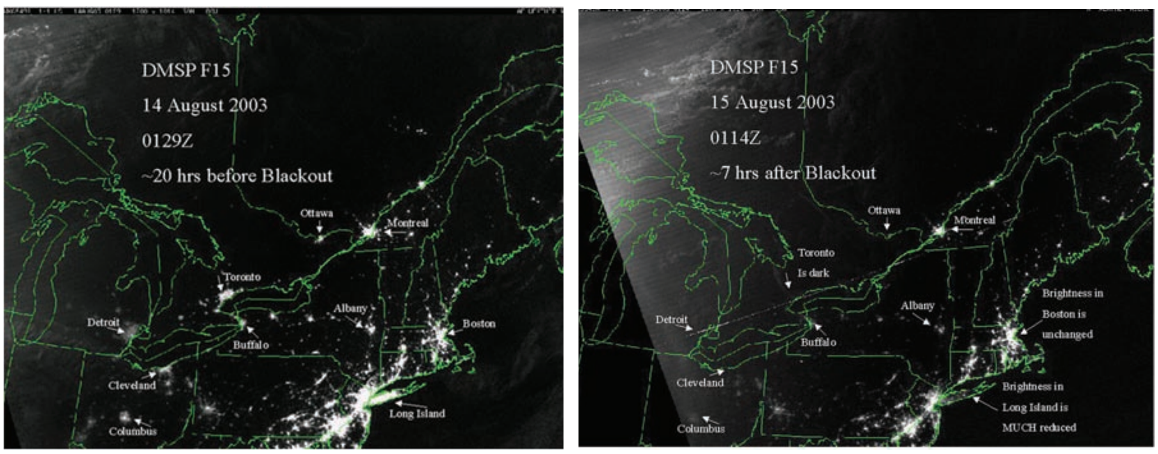
[52] For example, see DOT, Office of the Inspector General, 2005, "Status of FAA's major acquisitions: Cost growth and schedule delays continue to stall air traffic modernization," Report Number AV-2005-061, May 26; and Robert L. Glass, 2005, "IT failure rates—70 percent or 10-15 percent?" *IEEE Software* 22(3):112.

software; testbeds; repositories of software design and development knowledge and reference software; and new models of professional practice, education, and training.

Software is the product of practices and decision making that vary markedly with the individuals and groups doing the development and the organizational pressures (e.g., imposed by the marketplace) under which they labor. Developers do not have effective ways to model and visualize software complexity, including the possible range of interactions, especially unexpected and anomalous behaviors that can occur among software and hardware components. Developers also do not have time- or cost-effective ways to test, validate, and certify that software-based systems will perform reliably, securely, and safely as intended, particularly under attack or in partial failure. Education and training of software developers is inadequate, due in part to the frequent lack of state-of-the-art tools in the classroom.

The urgency of this effort is heightened by the emergence of multicore processors, which are in use today and which are expected over the next five years to become pervasive in computers – from mobile devices and desktops, which will be built using chips that contain tens of processors, to supercomputers, which will use millions to tens of millions of these multicore chips. These chips pose programming and system design challenges that must be addressed if their full potential is to be realized. The fundamental challenge is to develop efficient ways to write systems and application programs that can be broken into parallel sub-programs that make full use of the available number of processing cores such that their separate outputs can be integrated to generate the desired final output. Meeting that challenge will require the development of effective and efficient design methods and tools based on an understanding of the structure of systems and applications and the best ways to partition them for parallel execution.

Figure 5: Small Software Bug, Big Power Outage



The Northeast power outage in August 2003, which affected more than 50 million people in eight states and Canada, as shown in these satellite photos, was exacerbated by a software bug[53] *that prevented a warning about the initial, local outage from reaching other power companies that might have taken preventative action. (Images courtesy of the Air Force Weather Agency and the National Oceanic and Atmospheric Administration*[54])

[53] Kevin Poulsen, "Software Bug Contributed to Blackout," *Security Focus*, February 11, 2004, available at http://www.securityfocus.com/news/8016.

[54] http://www.noaanews.noaa.gov/nightlights/blackout081403-20hrsbefore-text.jpg and http://www.noaanews.noaa.gov/nightlights/blackout081503-7hrsafter-text.jpg.

Recommendation: The NITRD Subcommittee should facilitate efforts by leaders from academia, industry, and government to identify the critical issues in software design and development and help guide NITRD planning on software R&D.

The starting point of these efforts should be analyses of software issues.[55] A principal product should be research needs and planning documents. In addition, the PCAST encourages Federal agencies and industry to work together to provide undergraduate and graduate students in NIT fields with hands-on experiences in real-world software development environments through internships and fellowships.

DATA, DATA STORES, AND DATA STREAMS

NIT advances over the last few decades have made it possible to generate, transmit, and store information at rates and scales unprecedented in human history. Most new information is now "born digital," in text files, images, sound, video, multimedia, Internet telephony, process control signals, sensor recordings, and other forms of data. In 2006, about 160 billion gigabytes of information were created, stored, and copied, which is about 3 million times the information in all the books ever written. According to one analysis, that amount can be expected to increase six-fold by 2010.[56]

At the same time, the sheer volume of new data – the data deluge – is overwhelming the capacity of institutions to manage it and researchers to make use of it. The Federal science agencies alone now gather petabytes[57] of data annually and anticipate accelerating growth rates over the next five years.

Finding: The data deluge represents an opportunity to advance U.S. leadership in science and technology, and harnessing it has become a national priority. More robust NIT capabilities are needed to fully exploit large-scale data resources.

The ability to generate vast quantities of data is outpacing the development of infrastructures and tools adequate to support data-driven 21st century science and technology. The lag is understandable, given how rapidly the scale of digital data is growing. However, the work of rationalizing, organizing, and sustaining appropriate long-term infrastructures for significant data needs to be undertaken now. In the century ahead, print libraries for research and education must be matched by similar institutionalized infrastructures for scientific and other valuable digital data. Issues that need to be addressed include assignment of responsibility; costing and accountability for long-term management, maintenance, and preservation of data archives of national interest; challenges in federating archives; and policies for access to and use of data. This is the vision Vannevar Bush outlined in a prescient 1945 article[58] – about a data and knowledge indexing system that could augment human activities by making the relevant information available whenever needed.

The data infrastructure the PCAST envisions will most likely require several levels, including, at the national level, storage of high-value, irreplaceable data such as that obtained from observations of singular events or the results of R&D activities. These data need to be maintained and made accessible over generations of media, users, owners, and institutions. At another level, the infrastructure should enable scholars, students,

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[55] For example, see Daniel Jackson, Martyn Thomas, and Lynette I. Millett, editors. 2007. *Software for Dependable Systems: Sufficient Evidence?* Washington, D.C.: National Academies Press.

[56] John F. Gantz, et al., "The Expanding Digital Universe: A Forecast of Worldwide Information Growth Through 2010," IDC, March 2007, available at http://www.emc.com/about/destination/digital_universe/pdf/Expanding_Digital_Universe_IDC_WhitePaper_022507.pdf.

[57] A petabyte is over a million gigabytes.

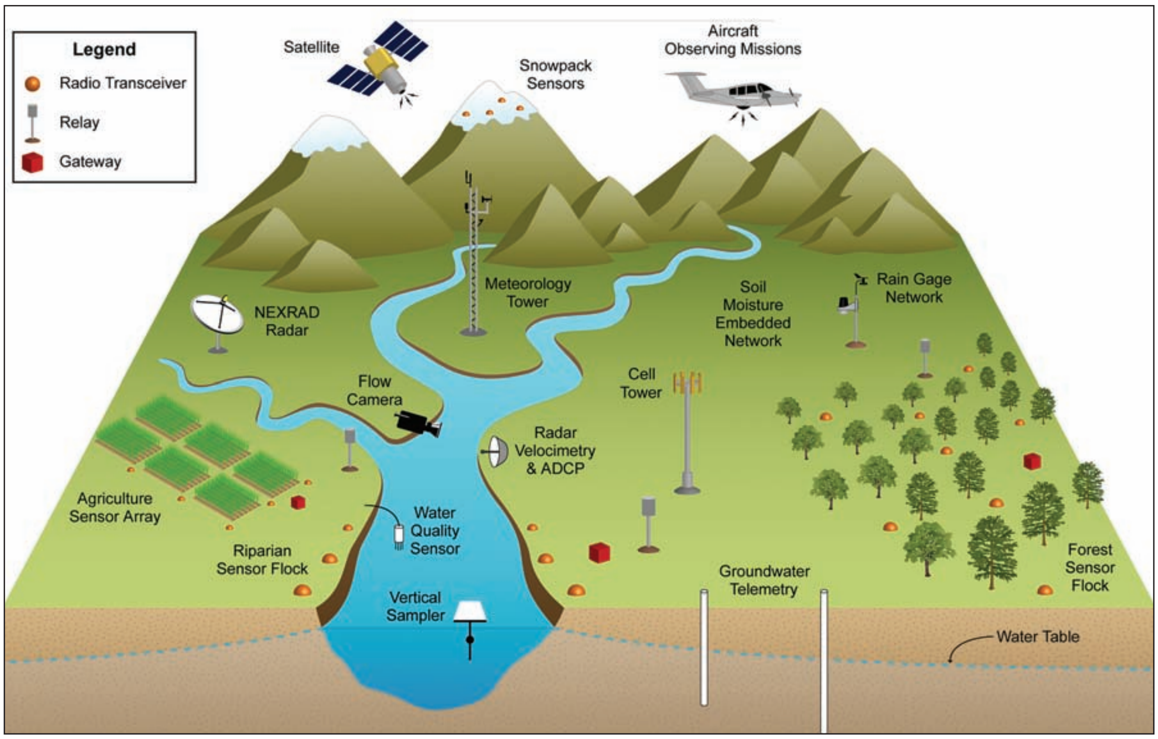
[58] Vannevar Bush, "As We May Think," *The Atlantic Monthly,* July 1945, pp. 101-108.

and industry users to identify and access regional, specialized, academic, and public-sector data collections. At each level, approaches and business models for supporting the data infrastructure over the long term need to be identified and incorporated into the planning process.

To be widely useful for research, development, and education, data infrastructures will require improved, user-oriented software for data management including provenance tracking, translation, mining, fusion, visualization, and analysis; automation technologies that make it easier to manage large-scale data sets; data and software interoperability methods, tools, and standards; and advanced, secure network connectivity between researchers and data stores that support high-volume data transfers.

The NITRD Program has long invested in NIT for collecting, storing, managing, and providing access to data and documents (e.g., the Digital Libraries Initiative[59]), but further investments are needed to develop full-scale support systems for data that are necessary for 21st-century research and education. Moreover, developing and managing large data repositories are not considered research activities themselves. Consequently, obtaining the sometimes substantial funding that may be needed can be difficult.

Figure 6: A Highly Instrumented Watershed



An instrumented watershed for the proposed WATERS Network[60] would continuously gather data from advanced sensor systems to be stored, managed, and made available for users studying, managing, and teaching about large-scale environmental systems. (Courtesy J. Fisher, University of California, Merced)

59 http://www.dli2.nsf.gov/ and http://www.dli2.nsf.gov/dlione/.

60 http://watersnet.org/index.html and R. Hooper for the WATERS Network Design Team, "WATERS Network: An Environmental Observatory Initiative of the U.S. National Science Foundation Engineering and Geosciences Directorates," *Geophysical Research Abstracts,* Vol. 9, 09231, 2007.

Recommendation: The Interagency Working Group on Digital Data, in cooperation with the NITRD Subcommittee, should develop a national strategy and develop and implement an associated plan to assure the long-term preservation, stewardship, and widespread availability of data important to science and technology.

Collaborators in this national planning process should include academia, professional and scholarly societies, curatorial institutions, national laboratories, foundations, and industry. As part of this effort, NITRD Program agencies should develop a multiagency R&D plan for managing and using data, which would include technologies and tools for data curation, trustworthiness assessment, data organization, usability, and interoperability; and user-oriented tools for mining, synthesis, fusion, analysis, and visualization.

NETWORKING

The Internet has become the world's basic communication fabric. Originally designed to serve a small number of researchers through a network architecture to support anticipated defense applications,[61] it has demonstrated a remarkable capacity to grow and evolve to accommodate global-scale needs.

However, the growth in Internet users and uses has led to problems that are serious today and expected to worsen as expansion continues. The architecture of the ARPANET, on which the Internet is based, assumes that the entities connected to it are in fixed locations and can be trusted; consequently, the design is open and vulnerable. Today, entities connected to the Internet face constant attacks that may be launched from anywhere in the world. Federal, State, and local governments, industry, and consumers already spend billions of dollars each year on preventing and recovering from attacks. The number of attacks and their potential to cause damage are both expected to rise in the years ahead. The connection of millions of mobile devices to the traffic load further stresses the Internet, increasing its fragility and the difficulty of managing its complexity.

Because vital interests of the United States now depend on secure, reliable, high-speed Internet connectivity, Internet vulnerabilities and limitations are a growing national security problem. They also complicate the development of next-generation networking applications that are important to Federal missions and society at large.

Mission-critical needs of Federal agencies that require Internet advances include mobile ad-hoc networks for emergency preparedness and response and battlefield applications; secure networking for critical infrastructures; static and dynamic sensor networks for environmental monitoring; and deployment of advanced national-scale applications to improve the quality of health care with privacy, security, and interoperability built in. Advanced Internet capabilities needed in scientific research include assuring high-speed transmission of large quantities of data from instrumentation and experimental facilities to storage sites, providing scientists with remote access to distributed data and tools, and enabling collaboration among large geographically (sometimes globally) distributed teams.

The Internet is continually undergoing incremental redesign and deployment, such as in the transition from one version of its underlying protocol to another and the transition from fiber to optical networking with its dramatically higher transmission speeds. By design, these improvements support legacy technologies and are largely invisible to users. The PCAST supports this evolutionary approach to increasing the capacity and

[61] Derived from *The Internet's Coming of Age.* Computer Science and Telecommunications Board. 2001. Washington, D.C.: National Academies Press.

capability of the Internet, but encourages the consideration of more extensive changes based, for example, on overlays to today's Internet.

Incremental improvement should move toward an Internet architecture that is more secure, effective, flexible, scalable, and resilient. With such improvements, the time and money spent today on administering network security policies and measures, patching vulnerabilities, and containing damage could be steadily reduced.

The Federal government has an overriding strategic interest in envisioning the future of U.S. networks and conducting fundamental R&D to develop new technologies, experimental models, and prototypes that point the way to a more secure, reliable, scalable, and robust Internet, while at the same time acknowledging the Internet's distributed and international nature. The Federal advanced networking R&D community has long interacted productively with the networking industry, and the efforts to improve the Internet will benefit from this continuing relationship.

Finding: U.S. leadership in advanced networking is a strategic national priority. The PCAST endorses the call by the Director of the Office of Science and Technology Policy for an interagency Federal Plan for Advanced Networking Research and Development.

Recommendation: A key element of the Federal Plan for Advanced Networking Research and Development should be an R&D agenda for upgrading the Internet. To meet Federal agency needs and support the Nation's critical infrastructures, the Plan should include R&D in mobile networking technologies and ways to increase network security and reliability.

HIGH-END COMPUTING

The modeling and simulation of large complex processes and products that are performed on high-end computing (HEC) systems provide strategic advantages to the United States in national defense, national and homeland security, U.S. scientific and technological leadership, and economic competitiveness.[62]

The United States is today the leader in HEC R&D, the installed base of HEC systems,[63] and software applications that require HEC capabilities. But other countries have challenged and continue to challenge that leadership. The U.S. Government is now and is likely to remain both the largest customer for the most capable HEC systems and the principal funder of HEC advances because HEC systems do not have the broad market potential of many other NIT technologies. However, the adoption by computer manufacturers of many ideas and technologies resulting from Federal HEC investments has contributed to overall U.S. leadership in computing.

As HEC capabilities improve and are better appreciated, the demand for access to HEC systems increases. For example, scientists can now use HEC to help engineer structures to survive earthquakes and to explore how the brain works – subjects not amenable to traditional laboratory methods or traditional computation.

To fully exploit these scientific opportunities and realize their economic and social benefits, however, the HEC community needs to address interrelated problems that inhibit growth in the numbers of HEC users across

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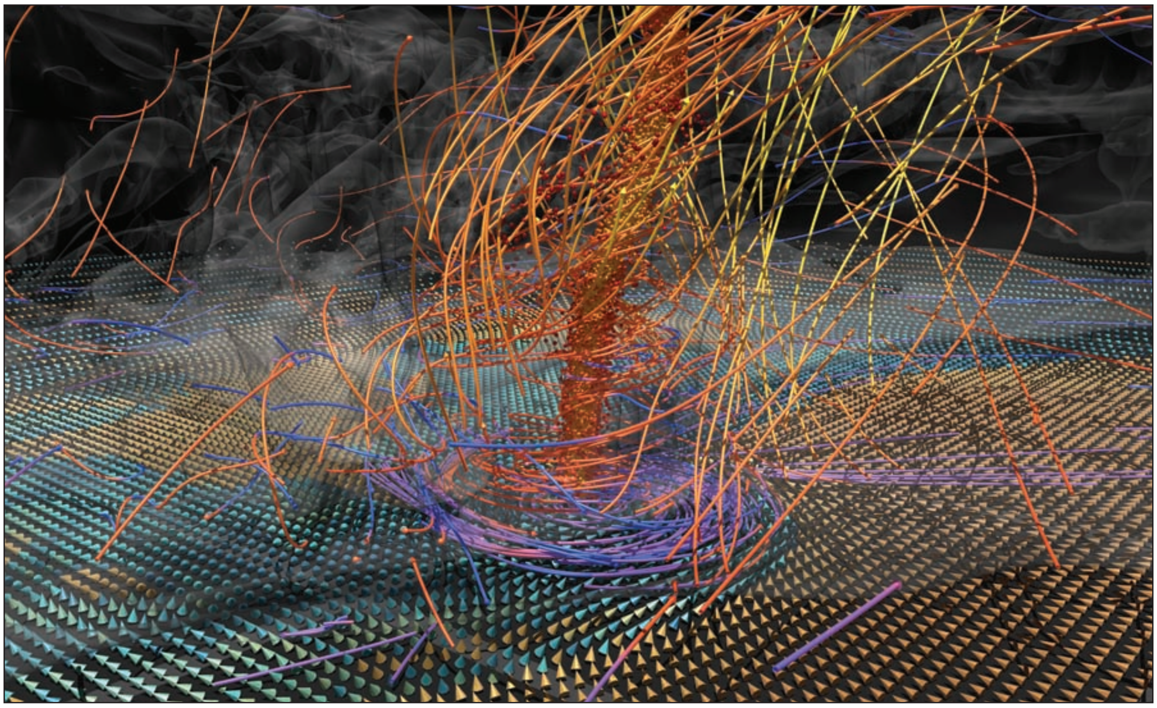
[62] *Computational Science: Ensuring America's Competitiveness*, President's Information Technology Advisory Committee, June 2005, available at http://www.nitrd.gov/pitac/reports/ 20050609_computational/computational.pdf.

[63] According to the June 2007 list of the Top 500 Supercomputers issued by the Universities of Mannheim and Tennessee and the Lawrence Berkeley National Laboratory, the United States was home to 281 of the 500 highest-performance supercomputers and no other nation had more than 30. Available at http://www.top500.org.

Figure 7: Tornado Simulation



This visualization of a tornado was created from data generated by a simulation calculated on an IBM p690 computing cluster at the National Center for Supercomputing Applications (NCSA). The tornado is shown by spheres that are colored according to pressure; orange and blue tubes represent the rising and falling airflow around the tornado. (Image courtesy of NCSA[64])

academia, industry, and government. The difficulty of using HEC system and application software is a disincentive for students and young professionals to apply them in their work. There are few tools to make it easier to work with HEC systems because of the limited business potential for developing software for small markets. As an initial step to address these problems, the HEC community should develop, maintain, and continually refine a collection of well-engineered software tools and software development environments that facilitate the use of HEC systems. Progress on addressing the HEC software challenge would be accelerated by progress on the general problem of software design and development, as described in the Software section above. These tools and environments should address the needs of the communities of scientists and engineers who will be the primary users of the HEC systems. As such tools and environments become increasingly accessible and available, greater numbers of users and applications will be able to take advantage of the power of HEC systems. By doing so, America's scientific and engineering communities and its industries will increase their competitive advantages.[65]

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[64] For information on the simulation see "Hunt for the Supertwister," Trish Barker, *ACCESS Magazine,* NCSA, November 2004. Available at http://access.ncsa.uiuc.edu/Stories/supertwister/index.htm. The tornado simulation and visualization were developed by Bob Wilhelmson, Robert Patterson, Stuart Levy, Matt Hall, Alex Betts, and Donna Cox, NCSA; Lou Wicker, National Oceanic and Atmospheric Administration; and Matt Gilmore and Lee Cronce, University of Illinois at Urbana-Champaign.

[65] Council on Competitiveness and the University of Southern California, The National Innovation Collaboration Ecosystem (NICE)SM. Overview available at http://www.compete.org/pdf/NICE_Overview.pdf.

Finding: High-end computing should remain a strategic national priority of the U.S. government.

The United States must continue to lead in the design, development, deployment, and use of the world's most capable computing systems. HEC technologies are complex and are still evolving rapidly and substantially, so HEC R&D must be sustained, flexible, and creative. To help ensure America's leadership in HEC, future generations of HEC researchers must be well educated and well trained.

Recommendation: The NITRD Subcommittee should develop, implement, and maintain a strategic plan for Federal investments in HEC R&D, infrastructure, applications, and education and training. Based on the strategic plan, the NITRD Subcommittee should involve experts from academia and industry to develop and maintain a HEC R&D roadmap.

These efforts should build on the 2004 *Federal Plan for High-End Computing*[66] and its implementation to date. They should also be responsive to the recommendations in the 2005 PITAC report entitled *Computational Science: Ensuring America's Competitiveness.*[67] The plan should:

- Address support for multidisciplinary teams of computer scientists, applied mathematicians, and discipline scientists and engineers using HEC to conduct long-term R&D on important national problems
- Address support for long-term operation of HEC R&D infrastructure, including maintenance of HEC software tools and programming environments and HEC applications and usage data
- Address the need for HEC architectures optimized to recognized important classes of applications
- Address the need for balanced Federal investments in HEC architectures, hardware, systems software, software tools and programming environments, and applications software
- Address the need for Federal investments in HEC education and training, including curricula that are adequate to ensure that the future needs for capable researchers, faculty, and practitioners will be met
- Address the need for organizational models that can enable more cost-effective development and support of HEC software
- Include steps for development and implementation of new metrics and measurements for assessing HEC systems

CYBER SECURITY AND INFORMATION ASSURANCE

The information infrastructure of the United States is a national asset, but its seemingly endless, costly, and potentially dangerous vulnerabilities also heighten the Nation's overall level of risk. Once computing systems – including those that monitor and control critical infrastructures, including national security systems – are connected to the Internet, they can present openings through which attackers located anywhere in the world can enter, compromise systems, and steal or corrupt information. Despite intensive efforts in government and the private sector in recent years to identify and patch vulnerabilities and to upgrade overall security, attackers continue to find new avenues for attack. (The Networking section in this chapter has a discussion of today's Internet.)

[66] National Science and Technology Council. *Federal Plan for High-End Computing.* Washington, D.C.: May 2004, available at http://www.nitrd.gov/pubs/2004_hecrtf/20040702_hecrtf.pdf.

[67] President's Information Technology Advisory Committee, op. cit.

Figure 8: Process Control Systems and Cyber Intrusions

The Linking the Oil and Gas Industry to Improve Cyber Security (LOGIIC) system monitors critical oil and gas industry process control systems for cyber intrusions. This photo shows two members of the LOGIIC team at Sandia's Center for Control Systems Security.[68] *(Source: Randy Montoya, Sandia National Laboratories)*

These security challenges are likely to become more severe as the scale and scope of Internet use expand – for example, with the connection of large numbers of sensors and other wireless devices – and as nation-states, terrorists, and criminal organizations seek to exploit the Internet's openness.[69] Secure NIT systems are central to the operation of key sectors such as banking, electronic commerce, health care, energy, and manufacturing, and thus the inability to maintain reasonable assurance adversely affects U.S. competitiveness as well as national security. Cyber security and information assurance (CSIA) is also important because of its inherent cross-cutting relevance to other areas within NIT R&D.

Finding: The ability to design and develop secure NIT systems is a national priority.

The current portfolio of Federal investments in CSIA R&D is too heavily weighted toward shorter-term projects and the development of reactive rather than preventative technologies. CSIA R&D should focus on developing the scientific and technological foundations for future-generation NIT systems that are inherently more secure than current technologies. The higher-priority investments for CSIA should include R&D in:

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[68] Details about the LOGIIC project are at http://www.sandia.gov/news/resources/releases/2006/logiic-project.html.

[69] For further discussion, see *Cyber Security: A Crisis in Prioritization,* President's Information Technology Advisory Committee, February 2005.

- Comprehensive analysis of potential system-level vulnerabilities to inform the design of inherently secure NIT systems
- Generation of the fundamental building blocks for the development of secure NIT systems
- Usability and related social sciences, because progress in improving the security of NIT systems also involves altering user behavior

Recommendation: The Federal NIT R&D agencies should give greater emphasis to fundamental, longer-term CSIA R&D and the infrastructure for that R&D.

The Federal NIT R&D agencies should accelerate development of an R&D infrastructure for creating, testing, and evaluating new generations of inherently more secure NIT systems. The PCAST also urges the agencies to accelerate interagency activities as specified in the *Federal Plan for Cyber Security and Information Assurance Research and Development.*[70]

HUMAN-COMPUTER INTERACTION

How people communicate instructions to computing systems, what computing systems provide in response, and how hardware, software, systems, and devices can be designed to do more to expand human capabilities is the broad and diversified portfolio of human-computer interaction (HCI) R&D. The PCAST highlights this area of NIT R&D as a priority because HCI technologies are necessary enablers of all NIT applications, transforming NIT's basic electronic processes into effective and efficient tools for human use. Advances in HCI R&D are needed to support progress in the other R&D priority areas cited in this chapter.

HCI research exemplifies one of the key themes of the PCAST's findings in Chapters 2 and 3. This area of NIT R&D is highly multidisciplinary, requiring the integration of technical expertise across a variety of disciplinary domains to achieve a complex engineered result. In HCI, researchers apply findings from the study of human behavior and physiology, including how people assimilate and use information, to the development of NIT technologies and systems that can augment human capabilities. Such HCI considerations are central in the development of an array of advanced capabilities, including autonomous robotic devices for national defense and national security applications. Advances in data visualization are required to make full use of scientific and other valuable data. HCI R&D in human-language processing such as capturing, transcribing, summarizing, and translating spoken and written language provides other essential capabilities.

More generally, as NIT systems grow in complexity, so does the need for more effective ways of understanding, managing, monitoring, and evaluating this complexity. The Federal NIT R&D agencies should give higher priority to fundamental investigation of technologies and tools to make NIT systems easier for people, including those with specialized needs, to use.

NIT AND THE SOCIAL SCIENCES

The 1999 PITAC report asserted that the domain of networking and information technology was transforming how Americans communicate, learn, work, and live. Those transformations have continued apace, as NIT systems are extended to ever-greater numbers of people and institutions around the world. Changes of similar magnitude are expected to continue into the foreseeable future. It is now clear that the interactions

[70] National Science and Technology Council, April 2006.

of these new technologies with people and organizations, and their frequently unforeseen or unintended consequences, pose challenges that are more social than technical.

Technologies powerful enough to change society should be accompanied by complementary investments in understanding and responding to their effects, to maximize benefits and minimize costs. The NITRD Program, which has been the primary source of funding for research examining the social science and social policy implications of NIT, should continue to invest in this multidisciplinary field to inform public understanding of NIT's societal benefits and costs, guide policy making, and point to new directions for NIT R&D over all. The following are a few of the many topics that deserve investment:

- *Information privacy* – analysis of concepts such as confidentiality, secrecy, access, and openness in an era in which vast amounts of information are readily available at little cost
- *Digital copyright* – analysis of mismatches between intellectual property mechanisms developed in the print age, especially copyright, and new capabilities that allow dramatic changes in the economics of content generation and diffusion, in contexts ranging from scholarly publications to entertainment products
- *Workforce changes and NIT workforce development* – empirical research on NIT workforce and development of new approaches to preparing the workforce that the country will need, and research on collaborative and distributed work and how to maximize its effectiveness
- *Economics of information* – analysis and models of transactions, markets, controls, and costs in a world of digital data
- *The digital society* – research on uses and consequences such as the digital divide, electronic voting, identity theft, Internet governance, and virtual worlds

Chapter 5

The Networking and Information Technology Research and Development Program

In the previous chapter, the PCAST provided recommendations about future technical directions of networking and information technology research and development. The NITRD Program is the entity primarily responsible for addressing these recommendations. This chapter focuses on the operation of the Program and the processes through which its 13 member agencies, its participating agencies, the Office of Science and Technology Policy (OSTP), the Office of Management and Budget (OMB), and the NITRD National Coordination Office (NCO) coordinate their activities to improve the quality, efficiency, and impact of the R&D in the NITRD Program. The PCAST also assessed the NITRD NCO, established in 1992 to support the Program's planning, budget, and assessment activities. The recommendations in this chapter describe how these organizations can better address the anticipated NIT R&D needs.

OVERVIEW OF NITRD PROGRAM PROCESSES

The High Performance Computing and Communications Program, now the NITRD Program, was chartered by Congress in the 1991 High-Performance Computing Act (Public Law 102-194). The purpose of the Act "is to help ensure the continued leadership of the United States" in NIT and its applications through Federal support for NIT R&D and applications; education and training; collaboration with Federal laboratories, industry, and universities; and interagency planning and coordination to "maximize the effectiveness" of the

NITRD Member Agencies

Agency for Healthcare Research and Quality (AHRQ)
Defense Advanced Research Projects Agency (DARPA)
Department of Energy/National Nuclear Security Administration (DOE/NNSA)
Department of Energy/Office of Science (DOE/SC)
Environmental Protection Agency (EPA)
National Aeronautics and Space Administration (NASA)
National Archives and Records Administration (NARA)
National Institute of Standards and Technology (NIST)
National Institutes of Health (NIH)
National Oceanic and Atmospheric Administration (NOAA)
National Science Foundation (NSF)
National Security Agency (NSA)
Office of the Secretary of Defense and DoD Service research organizations (OSD)

NITRD Participating Agencies

Department of Energy/Office of Electricity Delivery and Energy Reliability (DOE/OE)
Department of State (State)
Department of Transportation (DOT)
Department of the Treasury (Treasury)
Disruptive Technology Office (DTO)
Federal Aviation Administration (FAA)
Federal Bureau of Investigation (FBI)
Food and Drug Administration (FDA)
General Services Administration (GSA)
Technical Support Working Group (TSWG)
United States Geological Survey (USGS)

Government's efforts. The Act calls on the President to implement the Program, including establishing goals and priorities for Federal NIT R&D and providing for interagency coordination of this R&D. The Act calls on the Director of OSTP to submit an annual report on the Program's goals and priorities, programs and activities, funding levels, and progress; that report takes the form of a supplement to the President's annual budget request to Congress.

The multiagency NITRD Program, now in its 16th year, is unlike traditional Federal programs that are established, funded, and directed by a single agency. Rather, the Program is a framework for enabling diverse agencies to identify and articulate common NIT R&D goals, and to coordinate in planning, budgeting, and assessing their NIT R&D activities. In the PCAST's view, in general this framework has enabled the NITRD Program to respond quickly and effectively to rapid technological change and growth, albeit not without some challenges inherent in interagency coordination.

The NITRD Program has both *member agencies* and *participating agencies*. Agencies of both types engage in NITRD Program activities, but only member agencies report their NITRD budgets in the annual Supplement to the President's Budget.

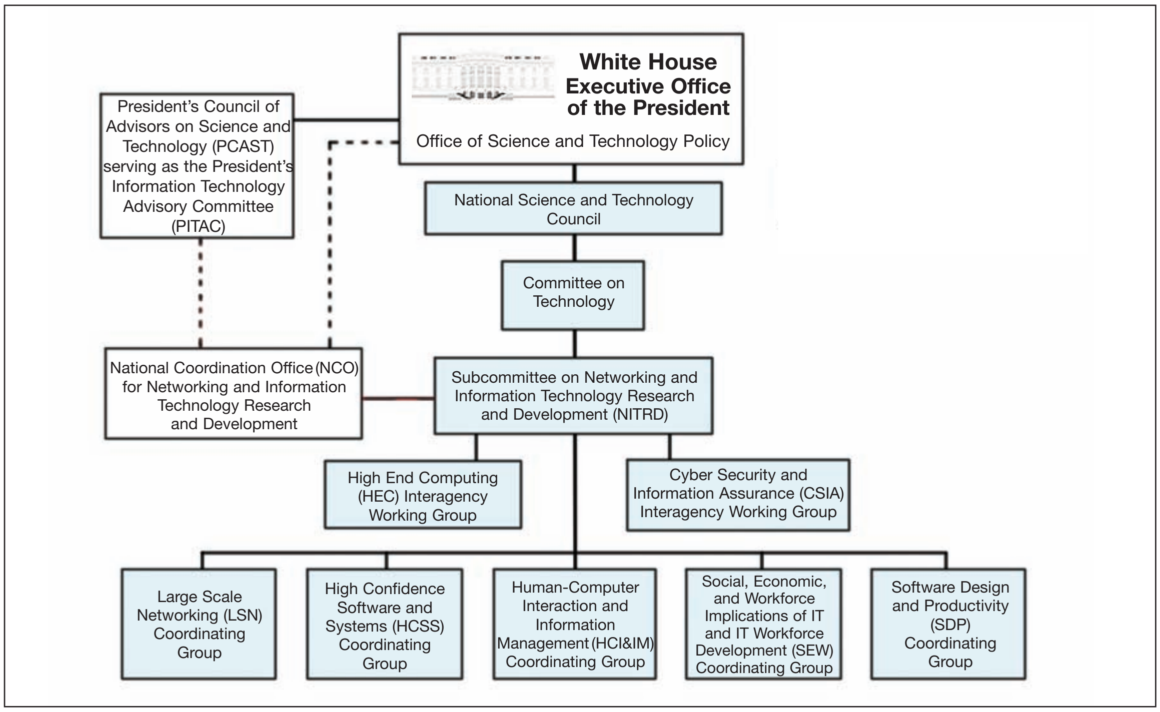
The Subcommittee on Networking and Information Technology R&D of the National Science and Technology Council's Committee on Technology guides overall NITRD Program coordination. Each NITRD agency designates a senior NIT R&D manager to serve on the NITRD Subcommittee, which also includes representatives of OMB, OSTP, and the NITRD NCO. The NITRD Subcommittee, which meets three times a year, approves NITRD Program organizational changes and sets policies and guidelines for NITRD activities. The NITRD Program is organized

Table 2: Agency FY 2008 NITRD Budget Requests by Program Component Area
(Dollars in Millions)

	High End Computing Infrastructure & Applications	High End Computing Research & Development	Cyber Security & Information Assurance	Human-Computer Interaction & Information Management	Large Scale Networking	High Confidence Software & Systems	Social, Economic, & Workforce Implications of IT	Software Design & Productivity	
AGENCY	**HEC I&A**	**HEC R&D**	**CSIA**	**HCI&IM**	**LSN**	**HCSS**	**SEW**	**SDP**	**Total***
NSF	303.1	67.1	69.2	225.6	106.7	57.4	109.3	55.3	993.7
OSD and DoD Service research organizations	234.1	2.0	23.3	78.7	137.4	31.5		4.3	511.4
NIH	131.7	1.8	1.2	194.5	65.4	8.2	11.9	2.9	417.6
DARPA		68.9	96.9	204.3	42.4				412.5
DOE/SC	250.5	67.0			47.3		5.0		369.8
NSA		60.3	15.8		1.4	25.2			102.6
NASA	71.4		0.3	8.0	1.5	3.5		2.0	86.7
NIST	2.4	1.8	11.1	8.4	5.3	19.7		5.1	53.8
AHRQ				39.8	5.0				44.8
DOE/NNSA	9.9	17.9			1.2		4.8		33.8
NOAA	16.4	1.9		0.5	2.9			1.6	23.3
EPA	3.3			3.0					6.3
NARA				4.5					4.5
TOTAL (2008 Request)*	**1,022.8**	**288.6**	**217.7**	**767.3**	**416.5**	**145.6**	**131.0**	**71.3**	**3,061**

* Totals may not sum correctly due to rounding.

Figure 9: NITRD Program Organization Chart



This figure depicts the Executive Branch organizations associated with the NITRD Program. NITRD Program funding also involves the U.S. Congress, which is responsible for appropriating funds for R&D, including for NIT, on an agency by agency basis each year.

into Program Component Areas (PCAs), both for formal budget purposes and to facilitate interagency coordination; coordination of activities in each PCA is carried out by an Interagency Working Group (IWG) or Coordinating Group (CG) made up of agency program managers. The FY 2008 NITRD Program budget table by agency and by PCA, which is included in the 2008 NITRD Supplement to the President's Budget, is displayed in Table 2. The relationships among the Executive Office of the President, the PCAST, the National Science and Technology Council, the NITRD Subcommittee, the organizations that report to the Subcommittee, and the NITRD National Coordination Office, are depicted in Figure 9.

THE NITRD PROGRAM SINCE 1999

Organizational Changes

The PCAST notes that the NITRD Program has made several changes in response to recommendations made in the first PITAC assessment of the NITRD Program, which was conducted in 1999, and to recommendations made in several topical PITAC assessments that were completed between 1999 and 2005.[71] (The Appendix contains a summary of the 1999 assessment recommendations and the PCAST's comments on the responses made by the NITRD Program.) Since 1999, the Program has added two member agencies – the Office of the

[71] See http://www.nitrd.gov/pubs/pitac/ and http://www.nitrd.gov/pitac/reports/.

Secretary of Defense and DoD Service research organizations and the National Archives and Records Administration – and a number of participating agencies. HEC has been divided into two PCAs to distinguish HEC R&D from HEC infrastructure and applications; three PCAs – Human-Computer Interaction and Information Management; High Confidence Software and Systems; and Social, Economic, and Workforce Implications of IT and IT Workforce Development – have expanded their scope and been renamed; and two PCAs have been added – Software Design and Productivity and Cyber Security and Information Assurance. The Federal Agency Administration of Science and Technology Education and Research (FASTER) Community of Practice, which was established to address operational and administrative issues of interest to NIT R&D agencies, reports to the NITRD Subcommittee.[72]

The NITRD budget has grown from approximately $1.5 billion in 2000 to approximately $3.1 billion in 2008.[73]

Information Development and Exchange

The NITRD Program develops and communicates information about its priorities and investments through the public release of reports that it is required to prepare. In addition, the Program identifies R&D needs by holding workshops and preparing associated reports.[74]

NITRD Supplements to the President's Budget. As called for by law, these reports to Congress provide supplemental information to the President's Budget request each year. The report describes current technical and coordination activities and plans for the next fiscal year for both member and participating agencies. The process of preparing the annual report entails substantial planning and information exchange among the agencies through their NITRD Subcommittee, IWG, and CG representatives and the NCO.

NITRD Federal Plans. The NITRD agencies have collaborated to produce two Federal R&D plans: the 2004 *Federal Plan for High-End Computing* and the 2006 *Federal Plan for Cyber Security and Information Assurance Research and Development.* Currently, an interagency task force is in the process of developing a Federal Plan for Advanced Networking R&D.

NITRD Grand Challenges Report. In 2003, the NITRD Subcommittee developed a report entitled *Grand Challenges: Science, Engineering, and Societal Advances Requiring Networking and Information Technology Research and Development* "to stimulate current and future generations of NIT R&D and applications researchers." The report identified national priorities, described illustrative grand challenges that contribute to one or more of the national priorities, and set forth "IT hard problem" areas in which advances are needed in order to solve the grand challenges. The IT hard problem areas align well with the technical areas in Chapter 4 of this report. The report was prepared in order "to *explain* why IT R&D is important to society, *justify* why public investments in IT R&D are necessary and desirable, and *galvanize* the NITRD agencies and the IT R&D community to solve IT hard problems."

NIT R&D Needs Workshops and Technical Reports. Since the 1999 PITAC assessment of the Program, NITRD agencies – working through the IWGs and CGs – have jointly sponsored national workshops that included academic and industry participants on key issues in NIT R&D and have published some of the results in

[72] The evolution of the NITRD PCAs can be found at: http://www.nitrd.gov/about/history/new-pca-names.pdf.
[73] The history of NITRD Program funding is available at http://www.nitrd.gov/about/history/nitrd_crosscut.pdf.
[74] NITRD reports are available at http://www.nitrd.gov/pubs.

technical reports. Together, the workshops and reports provide input to the agencies, communicate Federal research needs and interests to broader research communities, and foster new R&D directions.

As an example, in 2004 NITRD's High Confidence Software and Systems CG initiated a multiyear workshop series to draw national attention to the challenges of NIT systems connected with the physical world. The series is bringing together academic and industry researchers and Federal mission-agency program managers in illustrative application domains – medical devices, software, and systems; supervisory control and data acquisition systems; and aviation safety – as well as in cross-cutting issues such as an assured real-time operating system, with the goal of shaping a national R&D agenda to strengthen U.S. technical capabilities in these systems.

THE ROLE OF INFORMAL COORDINATION

The NITRD Program provides a framework and mechanisms that enable individuals responsible for their agencies' NIT R&D to quickly and directly leverage each other's knowledge and resources. Informally, agency participants serve as grant proposal reviewers for other agencies, attend other agencies' principal investigator meetings, participate in non-NITRD Federal task groups dealing with NIT issues as well as in national and international NIT R&D and standards-setting organizations, and contribute technical information to private-sector studies. These interactions often generate formal R&D collaborations. Informal interactions often emanate from IWG and CG meetings and activities, and such interactions also contribute to the formal coordination. In the PCAST's view, these informal interactions are essential to the success of the NITRD Program.

NITRD PROGRAM FINDINGS AND RECOMMENDATIONS

Finding: In general, the NITRD Program has effectively balanced the statutory mandates and mission requirements of the individual member agencies with government-wide needs and national priorities.

The PCAST finds that the extensive fabric of cross-agency collaboration developed through NITRD Program activities fosters positive outcomes such as:

- A common framework for identifying agency and government-wide NIT R&D needs and capability gaps
- A mechanism for the Federal government to meet its NIT R&D needs
- A means for agencies to identify other agencies with related needs and to work together to meet those needs
- Technological advances that meet multiple agencies' needs and the needs of the private sector

However, the most urgent and important challenges of developing and applying advanced NIT capabilities require larger-scale, longer-term, and multidisciplinary R&D. The processes, results, and outcomes of the NITRD Program must evolve if these multidimensional challenges are to be met.

Finding: The current nature and scale of the NITRD Program's coordination processes are inadequate to meet anticipated national needs and to maintain U.S. leadership in an era of global NIT competitiveness.

The PCAST's review of the NITRD Program revealed some weaknesses amid the Program's accomplishments. The Program has evolved from a small, novel experiment in cross-agency cooperation into a mature enterprise, and it is now well positioned to consolidate its strengths and address the formidable challenges of the future. The following recommendations are intended to support that process.

Recommendation: The Director of the Office of Science and Technology Policy should take steps to ensure broad and vigorous agency involvement in the NITRD Program, given its critical importance to national security and economic competitiveness.

The PCAST found considerable variation in the degree and nature of current agency participation in the NITRD Subcommittee and its IWGs and CGs. Although some variance is to be expected, given the widely differing missions of the NITRD agencies, from fundamental R&D to operational NIT applications, all NITRD agencies should place high priority on participation.

It is apparent to the PCAST that the interactions among agencies through NITRD involvement are beneficial to the Government's interest in accelerating NIT advances and optimizing the efficacy of Federal NIT R&D dollars. For the same reason, the NITRD agencies should be fully responsive to guidance in the annual OMB/OSTP memorandum on Administration Research and Development Budget Priorities and calls for R&D planning documents such as Federal Plans.

The PCAST recognizes the value of the NITRD Program's development of a strategic vision in a national context to explain technical goals, but such efforts must be more systematic and frequent in the future.

Recommendation: The NITRD Subcommittee should develop, maintain, and implement a cohesive strategic plan for the NITRD Program.

The PCAST found that while the NITRD Program has articulated both high-level general goals and research agendas in specific areas of NIT R&D, it lacks a comprehensive technology vision and strategy that identify the next generation and future generations of important NIT challenges and describe how to meet those challenges. The strategic plan should:

- Characterize the scope of the Program, especially in light of the increasing global competition in NIT
- Explicitly address the PCAST's recommendations on R&D priorities as described in this report
- Focus on collaborations across agencies, across PCAs, with academia and industry, and with international organizations to help ensure that the goals, plans, and activities both of agencies and of IWGs and CGs support a cohesive NITRD strategy
- Facilitate R&D transition both within and among agencies, such as from fundamental research to prototype hardware or deployable software
- Establish a mechanism for agencies to coordinate and fund large projects that cannot be easily divided among them; such coordination and funding may require the involvement of senior Federal policy makers
- Reflect the input of academic researchers, who are especially knowledgeable about what is possible in the short term and likely or desirable explorations in the long term
- Address accelerating the transition of NIT R&D knowledge and technologies to industry, especially because agencies need advanced NIT capabilities in the commercial products they procure
- Address international coordination, since many NIT capabilities are deployed worldwide

Developing this NITRD Program strategic plan may require augmenting or modifying the current high-level NITRD Program goals to include goals for individual PCAs and for R&D that spans PCAs.

The new strategic plan should be developed by the end of FY 2008. The NITRD Subcommittee should then hold annual planning and review meetings. The meetings should identify the current highest priorities for NIT R&D across agencies, emerging technical directions, and successes and areas of improvement for the NITRD Program. These meetings should include the review and revision of goals and metrics and the establishment of new ones. A summary of these meetings should be provided to OSTP, OMB, and PCAST.

Recommendation: The NITRD Subcommittee should conduct periodic assessments of the NITRD PCAs, restructuring the NITRD Program when warranted.

The assessments should determine whether the overall structure of the NITRD Program should be changed based on updated NITRD strategic plans, changes in national priorities, the rapid evolution of networking and information technology, and consideration of external input such as this report.

Recommendation: The NITRD Interagency Working Groups and Coordinating Groups should develop, maintain, and implement public R&D plans or roadmaps for key technical areas that require long-term interagency coordination and engagement. The plans and roadmaps should be developed under the guidance of the NITRD Subcommittee and be aligned with the NITRD Program's strategic plan.

In Chapter 4, the PCAST calls for developing R&D plans in several priority areas. Previous NITRD efforts to identify R&D needs in specific areas – through workshops and workshop reports – have helped stimulate national interest as well as inform and influence the broad R&D community. This recommendation calls on the NITRD Subcommittee to address those needs through a NITRD analysis, prioritization, and planning process for R&D areas deemed significant in advancing the Government's and Nation's NIT capabilities. The R&D plans should explicitly address related needs in education and training (including curricula), infrastructure for R&D, and technology transfer.

In some areas of the NITRD Program, it may be possible to supplement the R&D plans with more detailed technology R&D roadmaps. Areas of the NITRD Program that have a Federal Plan (High-End Computing and Cyber Security and Information Assurance) or are formulating one (Large Scale Networking) are candidates for the development of technology R&D roadmaps that include a list of research challenges with timelines for achieving progress toward meeting those challenges. Indeed, the Federal Plans themselves call for the development of R&D roadmaps. The *Federal Plan for High-End Computing* was published in 2004 and the *Federal Plan for Cyber Security and Information Assurance R&D* in 2006; however, no technology R&D roadmaps have yet been developed for these areas.

The NITRD IWGs and CGs should implement formal processes and schedules for creating and updating the roadmaps. They should also engage academia and industry on the roadmaps' technical content. The roadmapping should, wherever practicable, adopt the best practices of other successful technology roadmapping efforts. For example, the semiconductor industry devised the International Technology Roadmap for Semiconductors (ITRS) roadmap, an established and highly regarded roadmapping activity that is continually updated as the field changes.

The NITRD Subcommittee and the NITRD NCO should together plan how they will support not only the Program's strategic plan, R&D plans, and PCA assessments and revisions, but also the planning and coordination of larger, longer-term, multidisciplinary projects; greater interaction and coordination with academia, industry, and international entities; the planning of national workshops and preparation of workshop reports; and overall improved communication with all stakeholders.

Recommendation: The NITRD Subcommittee, with support from the NITRD NCO, should develop a set of metrics and other indicators of progress for the NITRD Program and use them to assess NITRD Program progress.

In general, these metrics and indicators should focus on outcomes rather than processes, have agreed-upon definitions, and be as few as possible, easy to measure, and amenable to measurement over time. They may be quantitative or qualitative. Metrics and indicators should be reviewed and improved as needed during periodic updates of the Strategic Plan.

To assess the balance of investment from basic research to systems development, the NITRD Subcommittee should estimate the funding within each agency for basic research and for applied research. This information will aid the assessment of NITRD investment in light of NITRD Program goals and agency missions.

ASSESSMENT OF THE NITRD NATIONAL COORDINATION OFFICE

As a part of its assessment of the NITRD Program, the PCAST assessed the NITRD National Coordination Office and its effectiveness in supporting the Program's mission. To inform this assessment, the PCAST commissioned the Science and Technology Policy Institute (STPI) of the Institute for Defense Analyses to ask representatives of the NITRD agencies as well as other NITRD and NCO stakeholders about their experience and satisfaction with the Office. STPI conducted 39 interviews with internal and external stakeholders of the Program. The results of those interviews helped inform the following findings and recommendations.

The NITRD National Coordination Office

The current primary responsibilities of the NITRD NCO are to provide:

- Technical and administrative support for the preparation of the annual NITRD Supplement to the President's Budget
- Technical support to OSTP on NITRD policy issues and to OMB on NITRD budget issues
- Technical and administrative support to the NITRD Subcommittee, two Interagency Working Groups, five Coordinating Groups, FASTER, and other NITRD organizations
- Technical and administrative support to the PCAST NIT Subcommittee
- Public information about the NITRD Program

Finding: NITRD NCO activities have resulted in increased NITRD interagency coordination and planning.

The NCO supports a variety of interagency R&D coordination and planning activities. Specifically, the NCO has supported the development of large reports such as the Federal Plans that provided platforms for new interagency collaborations. The High-End Computing University Research Activity and a new interagency collaboration in petascale computing are other examples of such collaborations. In addition, the NCO is instrumental in generating the annual budget supplement, which serves as a planning document for the NITRD agencies.

Finding: NITRD NCO activities have resulted in increased participation in conferences, workshops, and meetings by non-government experts that aid in identifying NITRD needs in strategic areas.

Each year, the NCO supports interagency workshops that stem from and support IWG and CG activities and needs. The workshops involve non-governmental stakeholders and are designed to gather input for planning. Some workshops result in publications or findings that serve as useful tools for articulating particular NITRD needs. Other workshops contribute to larger reports, such as the Federal Plans, which are cited as some of the most useful mechanisms for articulating NITRD needs. Given the value of such reports, the NCO and the Subcommittee should accelerate the process of preparing workshop reports.

Finding: The NITRD NCO is instrumental in facilitating communication among all stakeholders; however, the NCO could be more proactive in communicating with outside groups.

Recommendation: Under NITRD Subcommittee guidance, the NITRD NCO should develop and implement a plan for supporting the development, maintenance, and implementation of the NITRD strategic plan and R&D plans.

The NCO has been effective in its support of the interagency NITRD Program to date. However, the NCO will need to evolve to support the changes in NITRD Program activities and plans recommended above. The NCO should work with the NITRD Subcommittee to plan how it will support not only the Program's strategic plan, R&D plans, and PCA assessments and revisions, but also the planning and coordination of larger, longer-term, multidisciplinary projects; greater interaction and coordination with academia, industry, and international entities; the planning of national workshops and preparation of workshop reports; and overall improved communication with NITRD NCO stakeholders.

The PCAST recommends that the NCO serve as a repository of information that would facilitate future analytical evaluations of the NITRD Program and the NCO.

FUTURE ASSESSMENTS OF THE NITRD PROGRAM

It has been eight years since the last full assessment of the NITRD Program. The PCAST believes that this is too long and recommends that the NITRD Program be assessed by the body that is responsible for the duties of the President's Information Technology Advisory Committee at least once every three years. Following the release of this report, the PCAST will prepare a report on lessons learned from the process used in conducting this assessment. The report will describe the scope and structure of the assessment; the nature and usefulness of the various inputs, including the STPI global NIT competitiveness snapshot, briefings made to the PCAST/NIT Subcommittee, and surveys of the TAG; guidance from OSTP; and NCO support.

Appendix: Responses to the Recommendations in the 1999 PITAC Assessment

The PITAC's 1999 report entitled *Information Technology Research: Investing in Our Future* made 35 recommendations in four categories for government actions to improve the effectiveness of Federal NIT R&D. This section comments on the progress that the Government has made in addressing these recommendations.

The PCAST finds that Federal leaders and NITRD agency managers have made substantial efforts to address both the letter and the spirit of the recommendations. The Government has responded to many of them by developing new efforts and coordinating activities in R&D areas highlighted in the 1999 report. The Program's progress has been incomplete, not due to a lack of effort or intent but to substantive, organizational, and structural factors discussed elsewhere in *Leadership Under Challenge.* Most notably, the difficulty in rebalancing the mix of shorter-term, single-discipline, often incremental research with longer-term, larger-scale, multidisciplinary research and with innovative, higher-risk but higher-reward research remains largely unaddressed. This is the most critical challenge before us, as it will require structural changes in agency and university processes and behavior.

As the discussion in Chapter 4 suggests, progress in some areas of NIT R&D – for example, software, the 1999 report's top technical priority – is especially difficult. In its report, the PITAC said that software systems were then among the most complex structures engineered by humans. Software is even more complex today. It poses intellectual challenges at all levels, including software foundations, which take experience, understanding, creativity, and time to address. Perhaps equally telling is the fact that both research in and the creation of complex software challenge academic and government structures and management processes.

For each of the 1999 report's four categories, the sections below first summarize the PITAC recommendations and then provide PCAST comments on the Federal response.

PITAC Recommendations: Setting Federal Research Priorities

- Create a strategic initiative in long-term IT R&D
- Increase investment in research in software, scalable information infrastructure, high-end computing, and socioeconomic issues
- Fund projects of larger scope, longer duration, and by multidisciplinary teams

The PCAST's comments: The Government's responses to the first recommendation include expanding the scope of the Program, reflected in a more encompassing name – the Networking and Information Technology R&D (NITRD) Program – and raising its Federal and national visibility by consistently giving it a prominent position in the Joint R&D Priorities Memo from the Directors of the Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) to agency heads, and including the Program as a funding priority in the President's Budget. NITRD budgets in the areas noted in the second recommendation have been increased, as discussed in more detail below.

Some experiments in establishing formal programs to emphasize long-term, large-scale, and multidisciplinary research have been tried, with mixed success. Other PITAC recommendations for long-term research, such as the Expeditions to the 21st Century and Enabling Technology Centers (see management structure

recommendations below) remain unrealized. The PCAST's recommendations to rebalance the Federal NIT R&D portfolio are intended to address these issues.

PITAC Recommendations: Technical Research Priorities

- Make fundamental software research an absolute priority
- Make software research a substantive component of every major information technology research initiative
- Fund more fundamental research in software development methods and component technologies
- Support fundamental research in human-computer interfaces and interaction
- Fund more fundamental research in information management techniques to:
  (1) capture, organize, process, analyze, and explain information
  (2) make information available for its myriad uses
- Fund research in the behavior of the global-scale network and its associated information infrastructure, to include collecting and analyzing performance data as well as modeling and simulating network behavior
- Support research on the physics of the network, including optical technologies, wireless technologies including satellites, wired technologies including cable, and related bandwidth issues
- Support research to anticipate and plan for scaling the Internet
- Support research on middleware that enables large-scale systems
- Support research on large-scale applications and the scalable services they require
- Fund a balanced set of testbeds and research infrastructure that serve the needs of networking research as well as research in enabling information technologies and advanced applications
- Fund research into innovative computing technologies and architectures
- Fund R&D on software to improve the performance of high-end computing
- Drive high-end computing research by trying to attain a sustained petaops/petaflops on real applications by 2010 through a balance of software and hardware strategies
- Fund the acquisition of the most powerful high-end computing systems to support science and engineering research
- Expand the interagency coordination process in high-end computing (HEC) to include all major elements of the Government's investment in HEC

The PCAST's comments: There were both successes and failures in the Government's responses to these recommendations. Fundamental software research did not become the absolute priority of the Program, either in exploration of software development methods or in techniques for software security and reliability. Similarly, the Government has not put sufficiently high priority on issues in large-scale data and next-generation high-end computing architectures, with consequent competitive risks, as described in Chapter 4.

Structurally, however, the Program has sought to address the three technical areas emphasized by the PITAC – software research, scalable information infrastructure, and high-end computing. Software research now is conducted in all of NITRD's Program Component Areas (PCAs), and the fundamental science of software

development is funded through the Software Design and Productivity (SDP) PCA, created in 2001 in response to the PITAC report. In addition, the High Confidence Software and Systems (HCSS) PCA succeeded the former High Confidence Systems PCA to explicitly encompass software issues in its R&D agenda.

Similarly, research in human-computer interfaces and interaction and in information management techniques is addressed through the Human-Computer Interaction and Information Management (HCI&IM) PCA, which was created after the PITAC report by expanding the research portfolio of the former Human-Centered Systems PCA. Scalable information infrastructure recommendations are addressed through the Large Scale Networking (LSN) PCA, which includes research on the implications of large-scale (global) networks, Internet behavior, networking technologies including wireless and optical, middleware for large-scale applications and services, and testbeds and research infrastructure.

In response to the PITAC's HEC recommendations, the former High End Computing and Communications PCA was divided into two PCAs (HEC Research and Development [HEC R&D] and HEC Infrastructure and Applications [HEC I&A]) to more clearly document the scope of Federal HEC activities. These include R&D in innovative architectures and software for HEC, pursuit of the goal of petascale-system deployment by 2010 in cooperation with industry, and the development of coordinated acquisition strategies for leadership computing. Of particular note are the publication of an interagency *Federal Plan for High-End Computing,* and the establishment of a High-End Computing University Research Activity (HEC-URA) program for tackling specific software and software-development challenges to the effective use of HEC resources. In addition, in 2005 the HEC Coordinating Group (CG) was re-chartered as an Interagency Working Group (IWG) to reflect the rising strategic importance of the interagency activities in the two HEC PCAs, and OSD's High Performance Computing Modernization Program (HPCMP) and DoD Service research organizations joined the Program.

PITAC Recommendations: Socioeconomic Research and Policy Priorities

- Expand Federal initiatives and government-university-industry partnerships to increase information technology literacy, education, and access
- Expand Federal research into policy issues arising from information technology
- Fund information technology research on socioeconomic issues
- Expand the participation of underrepresented minorities and women in computer and information technology careers
- Create programs to remove the barriers to high-bandwidth connectivity posed by geographic location, size, and ethnic history of research and educational institutions and communities
- Accelerate and expand education in information technology at all levels – K-12, higher education, and lifelong learning
- Strengthen the use of information technology in education

The PCAST's comments: The recommendations about R&D on policy and socioeconomic issues of IT are directly addressed through the activities of the Social, Economic, and Workforce Implications of IT and IT Workforce Development (SEW) PCA, which was established in response to the PITAC report to broaden the research portfolio of the previous Education, Training, and Human Resources PCA. NITRD funding for R&D in the socioeconomic implications of NIT has increased substantially since 2000. The SEW agencies also fund scholarship and fellowship programs at the undergraduate and graduate levels to provide education and

training in such NIT fields as cyber security, computational science, and bio-informatics, and one NITRD agency supports formal programs to expand the participation of underrepresented minorities and women in NIT careers. The LSN PCA agencies have sponsored efforts to remove barriers to high-speed network connectivity at colleges and universities.

Other PITAC recommendations, such as providing IT resources to underserved communities for promoting literacy, education, and access, and expanding the use of IT in K-12 education, fall outside the scope of the NITRD Program but are addressed in other Federal programs.

Despite these programs and activities, the digital divide remains. Indeed, it has grown wider by some metrics, notably the base of student participation in NIT education and research. Efforts in these areas must remain a high priority.

PITAC Recommendations: Effective Management Structure for Federal IT R&D

- The National Science Foundation (NSF) should assume a leadership role in basic information technology research and be provided the necessary resources to play this role
- Designate a Senior Policy Official for Information Technology R&D
- Establish a senior-level policy and coordination committee to provide strategic planning and management
- Extend the NITRD Program coordination model to major Federal information technology R&D activities
- Fund collaborations with applications to drive information technology research, but take measures to ensure that research remains a primary goal
- Fund centers for Expeditions into the 21st Century
- Establish a program of Enabling Technology Centers
- Establish an annual review of research objectives and funding modes
- Increase funding for IT R&D over the fiscal years 2000-2004 by $1.37 billion

The PCAST's comments: The management recommendations have been implemented. In 2005, the former NITRD IWG was re-chartered as the NITRD Subcommittee, a senior-level coordinating body for the Program in the National Science and Technology Council. The NSF has demonstrated commendable leadership in the Program, co-chairing the NITRD Subcommittee and six out of seven of the IWGs and CGs. OSTP appoints a Senior Policy Analyst who is responsible for NIT R&D policy issues, and the Program has grown to include nearly all unclassified Federal NIT R&D. Collaborations with application domains are common across the NITRD PCAs, but the R&D in the NITRD Program remains focused on NIT. The increased funding goal was not fully achieved. The 2000 NITRD budget estimate was $1.5 billion; the 2008 NITRD budget request is $3.1 billion, which is a difference of $1.6 billion. A total of 12 agencies reported NITRD budgets in 2000; 13 agencies reported NITRD budgets in 2008.

Strategic interagency coordination remains a challenge, given the diverse missions of the NITRD agencies. Increased emphasis should be placed, possibly through structures such as the centers proposed by the PITAC, on coordinating the funding and implementation of larger, longer-term, multidisciplinary projects, which often have higher risk, and on the transition of technologies from basic research to prototyping and large-

scale evaluation. This transition mechanism can be successful only if the ecosystem's key components – government, academia, and industry – work more collaboratively and tightly over the long term.

The PCAST's conclusions: The participants in the NITRD Program took the PITAC report's recommendations seriously and have acted on a number of them in a substantive manner. In high-end computing, additional coordination and funding following the release of the *Federal Plan for High-End Computing* have enabled the NITRD agencies to make significant strides in addressing both R&D priorities and procurement issues. Likewise, the NITRD agencies involved in advanced networking R&D and in high-confidence software and systems R&D have made steady progress through consistently active engagement. Coordination is less evident in R&D in software development and in technologies and tools for information management. The CGs in these areas have struggled to formulate effective R&D coordination activities that can mobilize multiagency interest and resources over time. The PCAST addresses this issue in Chapter 5.

Three recommendations of the 1999 PITAC report have not been adopted, namely the establishment of an annual review of research objectives and funding modes, centers for Expeditions into the 21st Century, and a program for Enabling Technology Centers. These PITAC recommendations are addressed in Chapters 3 and 5, where PCAST emphasizes the importance of fundamental, qualitative changes in the scale and innovativeness of investments made in the NITRD Program. Without long-term, transformational research, the leadership position of the United States will remain at risk.

In PCAST's view, agency leadership of the NITRD Program – within the NITRD Subcommittee and its IWGs and CGs – must be more widely shared in order to meet changing needs due to the scale, scope, and complexity of NIT and NIT R&D; their single-discipline applications and new multidisciplinary applicability; and their growing strategic national importance.

Acronyms

AHRQ – Agency for Healthcare Research and Quality

AMD – Advanced Micro Devices

ARTEMIS – Advanced Research and Technology for Embedded Intelligence and Systems

BLS – Bureau of Labor Statistics

CG – Coordinating Group

CRA – Computing Research Association

CSIA – Cyber Security and Information Assurance, one of NITRD's eight Program Component Areas

DARPA – Defense Advanced Research Projects Agency

DoD – Department of Defense

DOE – Department of Energy

DOE/NNSA – DOE/National Nuclear Security Administration

DOE/OE – DOE/Office of Electricity Delivery and Energy Reliability

DOE/SC – DOE/Office of Science

DOL – Department of Labor

DOT – Department of Transportation

DRAM – Dynamic random access memory

DTO – Disruptive Technology Office

EPA – Environmental Protection Agency

EU – European Union

FAA – Federal Aviation Administration

FASTER – Federal Agency Administration of Science and Technology Education and Research Community of Practice

FBI – Federal Bureau of Investigation

FCRP – Focus Center Research Program

FDA – Food and Drug Administration

GAO – Government Accountability Office

GDP – Gross domestic product

GSA – General Services Administration

HCI – Human-computer interaction

HCI&IM – Human-Computer Interaction and Information Management, one of NITRD's eight Program Component Areas

HCSS – High Confidence Software and Systems, one of NITRD's eight Program Component Areas

HEC – High-end computing

HEC I&A – HEC Infrastructure and Applications, one of NITRD's eight Program Component Areas

HEC R&D – HEC Research and Development, one of NITRD's eight Program Component Areas

HEC-URA – HEC University Research Activity, jointly funded by multiple NITRD agencies

HP – Hewlett-Packard

HPCMP – High Performance Computing Modernization Program

ICT – Information and communication technology

IIT – Indian Institute of Technology

ITRS – International Technology Roadmap for Semiconductors

IWG – Interagency Working Group

LOGIIC – Linking the Oil and Gas Industry to Improve Cyber Security

LSN – Large Scale Networking, one of NITRD's eight Program Component Areas

NARA – National Archives and Records Administration

NASA – National Aeronautics and Space Administration

NCO – National Coordination Office

NCSA – National Center for Supercomputing Applications

NIH – National Institutes of Health

NIST – National Institute of Standards and Technology

NIT – Networking and information technology

NITRD – Networking and Information Technology Research and Development

NOAA – National Oceanic and Atmospheric Administration

NSA – National Security Agency

NSF – National Science Foundation

ODM – Original design manufacturer

OECD – Organisation for Economic Co-operation and Development

OMB – Office of Management and Budget

OSD – Office of the Secretary of Defense

OSTP – Office of Science and Technology Policy

PCA – Program Component Area

PCAST – President's Council of Advisors on Science and Technology

PITAC – President's Information Technology Advisory Committee

R&D – Research and development

SDP – Software Design and Productivity, one of NITRD's eight Program Component Areas

SEW – Social, Economic, and Workforce Implications of IT and IT Workforce Development, one of NITRD's eight Program Component Areas

SRS – Science Resources Statistics, a division of NSF

State – Department of State

STPI – Science and Technology Policy Institute

TAG – Technical Advisory Group

Treasury – Department of the Treasury

TSWG – Technical Support Working Group

USGS – United States Geological Survey

Y2K – Year 2000

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The United States leads the world in networking and information technology, but this leadership is under challenge. To sustain U.S. leadership, the Federal government should:

- Address the demand for skilled IT professionals by revamping curricula, increasing fellowships, and simplifying visa processes
- Emphasize larger-scale, longer-term, multidisciplinary IT R&D and innovative, higher-risk research
- Give priority to R&D in IT systems connected with the physical world, software, digital data, and networking
- Develop and implement strategic and technical plans for the NITRD Program

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